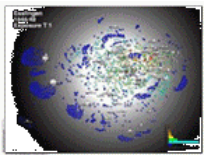

Peer Reviewed

Title:
Robust Intelligence (RI) under uncertainty: Mathematical foundations of autonomous hybrid (human-machine-robot) teams, organizations and systems

Journal Issue:
Structure and Dynamics, 6(2)

Author:
Lawless, William F., Paine College

Publication Date:
2013

Publication Info:
Structure and Dynamics, Social Dynamics and Complexity, Institute for Mathematical Behavioral Sciences, UC Irvine

Permalink:
http://www.escholarship.org/uc/item/83b1t1zk

Acknowledgements:
This material is based upon work supported by, or in part by, the U. S. Army Research Laboratory and the U. S. Army Research Office under contract/grant number W911NF-10-1-0252.

Author Bio:
Departments of Math & Psychology

Keywords:
interdependence, multi-tasking, competition, mathematical foundations

Local Identifier:
imbs_socdyn_sdeas_15715

Abstract:
To develop a theory of Robust Intelligence (RI), we continue to advance our theory of interdependence on the efficient and effective control of systems of autonomous hybrid teams composed of robots, machines and humans working interchangeably. As is the case with humans, we believe that RI is less likely to be achieved by individual computational agents; instead, we propose that a better path to RI is with interdependent agents. However, unlike conventional computational models where agents act independently of neighbors, where, for example, a predator mathematically consumes its prey or not as a function of a random interaction process,

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
2013		**00-00-2013 to 00-00-2013**

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
Robust Intelligence (RI) under uncertainty: Mathematical foundations of autonomous hybrid (human-machine-robot) teams, organizations and systems	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Paine College,Departments of Math & Psychology,1235 15th Street,Augusta,GA,30901**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

To develop a theory of Robust Intelligence (RI), we continue to advance our theory of interdependence on the efficient and effective control of systems of autonomous hybrid teams composed of robots, machines and humans working interchangeably. As is the case with humans we believe that RI is less likely to be achieved by individual computational agents; instead, we propose that a better path to RI is with interdependent agents. However, unlike conventional computational models where agents act independently of neighbors, where, for example, a predator mathematically consumes its prey or not as a function of a random interaction process, dynamic interdependence means that agents dynamically respond to the bi-directional signals of actual or potential presence of other agents (e.g., in states poised to fight or flight), a significant increase over conventional modeling complexity. That this problem is unsolved, mathematically and conceptually, precludes hybrid teams from processing information like human teams operating under challenges and perceived threats. To simplify this problem, we use bistable models for interdependence with a focus on teams and firms as we increase complexity to the level of systems. As part of the problem, in this paper, and countering simplification, sentient multiagent systems require an aggregation process like data fusion. But the conventional use of fusion for the control of mobile systems hinges on mathematical convergence into patterns increasing uncertainty whenever divergent information has the potential to process information into knowledge. The goals of our research are: First, to analyze why valid models of interdependence are difficult to build. Second, to reduce uncertainty in decision-making by moderating convergence processes in data aggregation (e.g., fusion) with differential clustering between alternative (orthogonal) views that check convergence processes and promote information processing (e.g., second opinions from independent physicians; prosecutor-defense attorneys; Republicans- Democrats in Congress; opposed scientists, like Bohr-Einstein). Third, in line with our theoretical expectations, we plan to lay the groundwork for agent-based systems to model the stability from the cooperative contexts associated with teams, and the instability from the competitive contexts associated with multiple teams or firms that constitute systems. Our result will be a new theory of interdependence; a new model of data aggregation; and new agent-based models of interdependence.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**Same as Report (SAR)**	**37**	

dynamic interdependence means that agents dynamically respond to the bi-directional signals of actual or potential presence of other agents (e.g., in states poised to fight or flight), a significant increase over conventional modeling complexity. That this problem is unsolved, mathematically and conceptually, precludes hybrid teams from processing information like human teams operating under challenges and perceived threats. To simplify this problem, we use bistable models for interdependence with a focus on teams and firms as we increase complexity to the level of systems. As part of the problem, in this paper, and countering simplification, sentient multi-agent systems require an aggregation process like data fusion. But the conventional use of fusion for the control of mobile systems hinges on mathematical convergence into patterns, increasing uncertainty whenever divergent information has the potential to process information into knowledge. The goals of our research are: First, to analyze why valid models of interdependence are difficult to build. Second, to reduce uncertainty in decision-making by moderating convergence processes in data aggregation (e.g., fusion) with differential clustering between alternative (orthogonal) views that check convergence processes and promote information processing (e.g., second opinions from independent physicians; prosecutor-defense attorneys; Republicans-Democrats in Congress; opposed scientists, like Bohr-Einstein). Third, in line with our theoretical expectations, we plan to lay the groundwork for agent-based systems to model the stability from the cooperative contexts associated with teams, and the instability from the competitive contexts associated with multiple teams or firms that constitute systems. Our result will be a new theory of interdependence; a new model of data aggregation; and new agent-based models of interdependence.

Robust Intelligence (RI) under uncertainty: Mathematical and conceptual foundations of autonomous hybrid (human-machine-robot) teams, organizations and systems

W.F. Lawless, Paine College, 1235 15th Street Augusta, GA 30901 wlawless@paine.edu	James Llinas, Research Professor (Emeritus) Department of Industrial and Systems Engineering Director (Emeritus), Center for Multisource Information Fusion State University of NY at Buffalo Buffalo NY 14260 llinas@buffalo.edu	Ranjeev Mittu, Branch Head Information Management & Decision Architectures Branch Information Technology Division U.S. Naval Research Laboratory 4555 Overlook Avenue, SW Washington, DC 20375 ranjeev.mittu@nrl.navy.mil http://www.nrl.navy.mil/imda/
Don Sofge, Navy Center for Applied Research in Artificial Intelligence Naval Research Laboratory 4555 Overlook Avenue S.W. Washington D.C. 20375 don.sofge@nrl.navy.mil	Ciara Sibley Engineering Research Psychologist Information Management & Decision Architectures Branch Information Technology Division U.S. Naval Research Laboratory 4555 Overlook Avenue, SW Washington, DC 20375 ciara.sibley@nrl.navy.mil	Joseph Coyne Engineering Research Psychologist Information Management & Decision Architectures Branch Information Technology Division U.S. Naval Research Laboratory 4555 Overlook Avenue, SW Washington, DC 20375 joseph.coyne@nrl.navy.mil
Stephen Russell, Computer Scientist Information Management & Decision Architectures Branch Information Technology Division U.S. Naval Research Laboratory 4555 Overlook Avenue, SW Washington, DC 20375 stephen.russell@nrl.navy.mil		

Abstract

To develop a theory of Robust Intelligence (RI), we continue to advance our theory of interdependence for the efficient and effective control of systems of autonomous hybrid teams composed of robots, machines and humans working interchangeably. As is the case with

humans, we believe that RI is less likely to be achieved by individual computational agents; instead, we propose that a better path to RI is with interdependent agents. However, unlike conventional computational models where agents act independently of neighbors, where, for example, a predator mathematically consumes its prey or not as a function of a random interaction process, dynamic interdependence means that agents dynamically respond to the bi-directional signals of actual or potential presence of other agents (e.g., in states poised to fight or flight), a significant increase over conventional modeling complexity. That this problem is unsolved, mathematically and conceptually, precludes hybrid teams from processing information like human teams operating under joint challenges and perceived threats. To simplify this problem, we use bistable models for interdependence with a focus on teams and firms as we increase complexity to the level of systems. As part of the problem, in this paper, and countering simplification, sentient multi-agent systems require an aggregation process like data fusion. But the conventional use of fusion for the control of mobile systems hinges on mathematical convergence into patterns, increasing uncertainty whenever divergent information increases the potential to process information into knowledge. The goals of our research project are: First, to analyze why valid models of interdependence are difficult to build. Second, to reduce uncertainty in decision-making by moderating convergence processes in data aggregation (e.g., fusion) with differential clustering among alternative (orthogonal) views that check convergence processes and promote information processing (e.g., second opinions from independent physicians; prosecutor-defense attorneys; Republicans-Democrats in Congress; opposed scientists, like Bohr-Einstein). Third, in line with our theoretical expectations, we plan to lay the groundwork for agent-based systems to model the stability from the cooperative contexts associated with teams, and the instability from the competitive contexts associated with multiple teams or firms that constitute systems. If successful, our results will be a new theory of interdependence; a new model of data aggregation; and a new agent-based model of interdependence.

Keywords: interdependence; multi-tasking; competition; mathematical foundations

Editor's Note Math Professor William Lawless is an America Hero, "Whistleblower Extraordinaire," Reprinted from Canadian Coalition for Nuclear Responsibility (CCNR):

"At Savannah River, South Carolina, the US Department of Energy ran plutonium production reactors (to make plutonium for bombs) and a reprocessing plant (to separate plutonium from spent nuclear fuel). William Lawless was surprised when -- with no prior experience -- he was put in charge of radioactive waste management at the huge military complex. He wanted to do a good job, so he started asking some pointed questions: why were liquid radioactive wastes being poured into shallow trenches, where they could leak into the soil and enter the surface waters? Why were solid plutonium-contaminated wastes being buried in cardboard boxes and covered with earth? He was told to keep quiet. Instead, he went public, and promptly lost his job. He was hired to teach mathematics at a local college, which enabled him to make a living while he kept on talking -- to the press, on national radio and TV -- about shoddy waste management practices at Savannah River. Since then, all plutonium production reactors and reprocessing plants have been shut down not only at Savannah River but also throughout the US, and environmental cleanup has become a priority. The US Congress has been told that radioactive cleanup and decontamination at military nuclear facilities in the US will cost over $200 billion -- more than twice the cost of the Vietnam War."

Overview

Our research proposes a solution for dynamic interdependence under uncertainty that more closely models human cognition and behavior, guided by the mistakes common to both. If successful, the result should be improved metrics for and mathematics of hybrid teams, firms and systems of teams and firms performing under uncertainty. An established mathematics of teams would lead to the ability to improve trust among humans, machines and robots. An integral part of our solution, an improvement in the process of data aggregation and analyses by including interdependence, would advance the science of data fusion and decision-making. Finally, a valid computational model of interdependence would advance the physics of the natural limits in understanding of organizational science; economics of systems of firms; and the computational science of hybrid teams, firms and systems.

Introduction

Our challenge is to devise a valid theory for hybrid teams composed interchangeably of humans, machines and robots. We propose that Robust Intelligence (RI) for humans occurs under states of interdependence, becoming more robust as social groups scale in size. However, dynamic interdependence has not been solved for human teams, which we review below, making it an attractive problem for RI. Hybrid teams should be capable of solving the problems that human teams solve innately; but despite great strides, the theory of human teams, firms and systems of firms remains elusive (e.g., Bell et al, 2012), let alone their mathematics, pushing the reality of hybrid teams into the distant future.[1] We propose that the search for energy by human agents is a better organizing principle than traditional game theory that will lead to the solution of multitasking and teams innately solved by humans, which we outline herein. Mistakes made and avoided figure naturally into how this principle unfolds.

Despite recognizing that modern organization theory has failed (Pfeffer & Fong, 2005), we have long struggled to develop a theory of organizations based on interdependence under uncertainty (Lawless et al., 2007). We stumbled onto this problem when addressing the causes of the widespread contamination across the USA by the Department of Energy's (DOE) mismanagement of its nuclear wastes;[2] we attributed DOE's mistakes to its lack of competition from scientific and social checks and balances even though DOE had many of the world's top nuclear scientists and engineers in its employ (Lawless et al., 2008). Some of our ideas have since been the subject of or reviewed in symposia.[3] The mathematical models that we have developed to date support the proposition that dynamic interdependence is a critical factor for hybrid human-machine-robot teams and as hybrid teams scale to organizations and systems. Our goal fits with Gluck's (2012) description that "It is clear the traditional boundaries between human and machine are disappearing. … especially in complex and uncertain dynamic environments." But even as these boundaries disappear, the theory of teams remains unsolved for humans (e.g., Bell et al., 2012).

---

[1] Controversy is brewing over whether robots should be allowed to become as intelligent as humans; e.g., see Keller, B. (2013, 3/16), "Smart drones", *The New York Times*.

[2] The first author blew the whistle against DOE in 1983; reviewed in Lawless et al., 2010.

[3] For example, two of the coauthors co-organized a Spring Symposium with AAAI at Stanford in 2012 on "Aggregation and Autonomy with Hybrid Agent Groups" (www.aaai.org/Symposia/Spring/sss12symposia.php); and the AAAI Symposium at Stanford in Spring 2013 on "Trust with Autonomous Systems" (www.aaai.org/Symposia/Spring/sss13.php)

As an eventual application, we are concerned with metrics of performance for hybrid teams and larger units, composed interchangeably of humans, machines and robots. First, we define and scale the effects of interdependence under uncertainty among teams, organizations (or firms), and systems. As these units scale from teams and organizations to society, interdependence is critical to outcomes (Smith & Tushman, 2005). Second, we bring an information theoretic approach to the metrics of interdependence at each scale (Conant, 1976). Third, we use biological and quantum models that capture different aspects of dynamic interdependence mathematically. And fourth, we consider the problems that interdependent agents address as either well defined and complete, or as ill posed and intractable. To date, for problem sets that are well-established or where uncertainty has been reduced to knowledge (i.e., when the eigenvalues for two competing team state vectors A and B are the same, or $[A,B]=0$;[4] in this case, competing teams arrive at the same solution; e.g., like the USA and Soviet Union did over Mutually Assured Destruction), we have concluded that teams, and, to a large extent, organizations work best under rules that promote cooperation and consensus (Lawless et al., 2011). However, when problem sets are intractable, ill-posed, or well-defined but operate in uncertain environments, we have concluded that competition among different worldviews best serve public welfare (i.e., a "gap" in the estimation of social reality exists, implying that $[A,B]=iC$;[5] e.g., discussed below, Smallman, 2012, concluded that bringing alternative viewpoints into decision-making may reduce accidents).

Why is our problem important?

Another conclusion by Lawless and his colleagues (2010) is that the measurement of interdependence under uncertainty always produces incomplete information, reducing the value of observations. This finding alone raises significant problems with the generation of information for metrics. It adds uncertainty to interpretation and meaning, making them forever elusive, an added, unexpected complexity. Yet, despite this complexity in understanding, we propose that if humans can successfully work with interdependent uncertainty, which they do every day, it is mathematically tractable. Our purpose in writing this progress report is to sketch the mathematics that reflects what we have found.

We have also found that many of the problems confronting groups today are linked with our research. To illustrate, group survival depends on the multitasking skills of a team or firm to find, obtain and store free energy (ΔA) by competing against opponents in part by seeking to gain

[4] For a brief tutorial of the mathematics involved, see the Appendix after the Reference Section.

[5] Combining alternative perspectives generates a phase space that captures a limit cycle. Turchin (2005) illustrates the phase space for warfare and state strength (p. 3) that recurs at generational time lags in how the amelioration of social disruption improves a population density/resource ratio; conversely, at generational time lags, the population density/resource ratio amplifies social disruption. Shifts in cycles may precipitate rapidly between generations, with increasing intervals to the next intergenerational event. Over long periods, an empire's stable cycle is in turn disrupted by migration or external wars, resulting in cycle variability: "we should not expect rises and falls to succeed each other with a high degree of regularity" (Turchin, 2007, p. 209); nonetheless, the evidence indicates that the "…stability and internal peace that strong empires impose contain within it the seeds of chaos. Stability and internal peace bring prosperity; prosperity causes population increase. Demographic growth leads to overpopulation; overpopulation causes lower wages, higher land rents, and falling per-capita incomes … [Eventually, the] collapse of order brings … famine, war, pestilence, and death. Population declines … civil wars thin the ranks of the elites … Intra-elite competition subsides, allowing order to be restored. Stability and internal peace bring prosperity, and another secular cycle begins." (p. 207).

a knowledge of their robustness (Lawless et al., 2010). Failure to maintain robustness leads to collapse, even for well-established firms.[6] Interestingly, while robustness is measured by the response to perturbations (Gluck et al., in press, p. 193), responses to perturbations provide indirect information that an outside group of observers seeks to convert into the knowledge that helps in the struggle to survive against opponents. Like a football team that attacks (perturbs) one side of its opponent's line and then the other, a target's response to a perturbation can be observed by the attacking team--or by larger units in a system, such as with mergers and even when the opponents are nation states.[7] Information is generated by responses to perturbations that illustrate the robustness or fragility of an opponent that can then be observed and exploited (Taleb, 2012); exploiting this effect, a military feint is a "response" that generates information to distract or mislead an opponent; or deception is used by a prey to not act when perturbed even as a predator is seeking to provoke a response.[8]

We remain surprised with our own claim that measuring dynamic interdependent information is always incomplete (Lawless et al., 2011), but it does account for misjudgments with the information gained (where knowledge implies a lack of uncertainty; Conant, 1976). Israel's fight against Hamas is an example of misjudging an opponent's robustness: "the Jewish state had an opportunity to strike a decisive military blow but declined ..."[9] Moreover, this example is strikingly similar to the lack of a decisive blow against tuberculosis (TB), allowing it to evolve and strengthen.[10] Other examples of misjudging an opponent's or ones own group's robustness are readily found in politics[11] and technology.[12] Misjudgments can come from incorrect attempts to strengthen robustness under uncertainty, with, for example, the authoritarian grab for power to dampen signals of robustness from opponents, beginning anew in Egypt;[13] but authoritarianism, as in China, for example, has reduced the health robustness of both opponents and leaders as well as citizens.[14] Mistakes from misjudgments are common in business with mergers designed to make a firm more competitive in uncertain environments, exemplified by H-P's merger failures, especially when compared to Oracle's success.[15] As a classic example of a perturbation that gained knowledge, Oracle acquired PeopleSoft in a hostile merger that succeeded despite the struggle by PeopleSoft to defend itself.[16]

Despite Oracle's past successes, in general, successful mergers reduce volatility, but they also limit the ability to innovate, making firms fragile and dependent on newer merger targets (fragility is defined as the lack of robustness; see Gluck et al., 2012, p. 204). As the leader in its market, Oracle's size exemplifies this problem:

---

[6] *Latinos Post* (2012, 11/22), "Hostess Going Out Of Business - Nov. 22 2012 Update: Company Will Liquidate Immediately, Fires 15,000 Workers on Day Before Thanksgiving", http://www.latinospost.com/articles/7203/20121122/hostess-going-out-business-nov-22-2012.htm

[7] *Christian Science Monitor* (2012,12/13), "Japan scrambles F-15s after China flies over disputed islands".

[8] *National Geographic* (2012, December), "The art of deception. Sometimes survival means lying, stealing, or vanishing in place." http://ngm.nationalgeographic.com/2009/08/mimicry/ziegler-photography

[9] *Wall Street Journal* (2012, 11/23), Hamas's Gaza victory", wsj.com.

[10] *Wall Street Journal* (2012, 11/23), "How fight to tame TB made it stronger", wsj.com.

[11] *Wall Street Journal* (2012, 11/23), "Tea Party seeks to regroup", wsj.com.

[12] *New York Times* (2012, 10/23), "[Microsoft's] Sleek tablet, but clumsy software", nytimes.com.

[13] *Wall Street Journal* (2012, 11/23), "Egypt's President solidifies power", wsj.com.

[14] *Bloomberg* (2013, 1/12), "Beijingers Told to Stay Indoors as Pollution Hits Record." Also, *New York Times* (2013, 3/22), "As pollution worsens in China, solutions succumb to infighting."

[15] *Wall Street Journal* (2012, 11/23), "Oracle shows H-P how to do acquisitions", wsj.com.

[16] Daines et al., 2006, "Oracle's Hostile Takeover of PeopleSoft", *Harvard Business Review*, http://hbr.org/product/oracle-s-hostile-takeover-of-peoplesoft-a/an/CG4A-PDF-ENG

> Oracle remains a dominant force in technology with $32.7 billion in revenue and database and applications software used by corporations to manage their finances and procurement. Today, [however,] its business is being eroded at the edges by smaller, more focused companies offering newer technology." (p. B1-2).[17]

In addition to an increase in stability, among other reasons to merge are to reduce costs, to decrease competition, to innovate to stay ahead of competitors, and to be able to increase prices in a less competitive market.[18]

The difference between efficiency and effectiveness and its relation to robustness is being studied (e.g., at the cellular level, see Chandra et al., 2011). We have sought to apply some of the lessons learned at the level of firms. For example, the problem with increasing organizational efficiency is that it reduces the opportunity for innovation; e.g., General Electric has been a leader with 6-sigma processes, but in 2012, GE was listed 90th on the Forbes Top 100 Innovators list.[19] Smith and Tushman (2005) have concluded that innovation requires tension across an organization or system, especially between competing objectives (viz., increase efficiency, increase innovation). Thus, the effort to increase efficiency potentially impedes the desire to improve say the practices of science that increase the likelihood of scientific innovations. But, as we have proposed in the past, when large systems of organizations mindfully adopt these two conflicting goals, the system overall becomes more efficient and innovative (Lawless et al., 2011). With our research, we hope to make a stronger connection between our research on hybrid human-machine-robot teams and robustness, fragility, and the costs to adapt and evolve (Lawless, 2012). We hope that our research will contribute to the quantification of and metrics for robustness (e.g., Walsh et al., submitted).

We propose to revise interdependence around Available Energy and mistakes

We have concluded that the traditional model of interdependence is static, especially in game theory. Instead of static configurations of interdependence around which games are structured, we propose that an improvement is to organize models around the interdependent search for sources of energy (E) and the mistakes that arise during these searches. For example, a mistake societies often make is to fully exploit a resource, leading to social collapse when the resource becomes depleted (Turchin, 2005), mitigated somewhat by new technology (White, 2007).

Individual agents need sufficient free energy to survive, providing for basic needs such as shelter, food, defense, and perceived other needs. But the physical environment is uncertain and ever changing, requiring exploration to search and acquire the free energy (ΔA) resources large enough to defray the costs of survival. Compounding physical uncertainty is the social uncertainty derived from interdependence, a social or bidirectional signal expressed as mutual

[17] Wall Street Journal (2013, 3/22/13), "New rivals clip Oracle's wings.'

[18] *Wall Street Journal* (2012, 12/20), "ICE in deal to buy NYSE", wsj.com. The bid by ICE for NYSE was $8.2 billion. NYSE handles primarily stocks, ICE primarily options. Interestingly, the NYSE can trace its origins to 1792, ICE only to 2000; the NYSE is worth $5.8 billion today, ICE $9.3 billion; and while ICE deals primarily in options, NYSE averages more than $150 billion in stock trades each day for firms with an estimated worth of $14.24 trillion. However, the actual target of ICE was the UK's Liffe firm, owned by NYSE. Liffe deals with income futures, a market that ICE has expressed an interest in entering.

[19] With a market value of $415 billion in 2000, GE was ranked as one of the most innovative, competitive and largest firms in the world (e.g., *Investors Business Daily*, 2000, 10/31; Bloomberg's *Businessweek*, 2001, 9/9); today, its market value is listed by the NYSE at $219 billion (*NYSE*, 2013, 1/8).

dependence common to human organization (Smith & Tushman, 2005). To explore both environments, an individual uses sensors that continuously collect and update physical and social data. At each moment in time, this data is aggregated (fused) and evaluated based on signal strength and individual experience, but with the latter able to constrain or overwhelm the former, increasing the likelihood that misperceptions like illusions will govern individual decisions (Adelson, 2000), producing mistakes.

To govern itself and its struggle to survive, uncertainty forces an individual to estimate its needs with real and perceived costs, adding to the likelihood that mistakes can occur. Mistakes can be minimized with strategies to reduce uncertainty and subjectivity. Strategies are weakened by the inability of individuals to multitask, offset when individuals exploit interdependence by working together in teams (Ambrose, 2001), but multitasking reduces adaptability. Team mistakes can be reduced with collective decisions (Sasaki & Pratt, 2011). Collective mistakes can be reduced with feedback from individuals, teams and collectives, but feedback at each level can be corrupted or manipulated; e.g., leaders and dictators censor information to maintain social control (May, 1973); shady investors create the illusion of safety;[20] and politicians purposively mis-characterize opponents (Coleman 2003).[21] However, humans have discovered that the orthogonal information developed between teams or firms if free to flow, as in democracies, can reduce the harm from attempts to manipulate data (Lawless et al., 2011). But while the goal of humans and human society remains survival, uncertainty and mistakes complicate the task at every step.

Hybrid Teams: Why are hybrid teams a challenging problem?

In this paper, we report past progress on developing theory to solve two computational problems with systems of agents in states of interdependence: cooperation and competition. We have found that cooperation works best in improving the multi-tasking operations of teams and larger groups, like organizations; e.g., operant conditioning to improve multi-robot team stability with rewards and punishment or negative feedback; 6-sigma methods to reduce organizational waste and improve productivity; and processes that encompass upgrades in talent and technology, including mergers and acquisitions to strengthen or replace weak or failing firms.[22] In contrast, we expect competition to work best for operations between teams, or organizations, or in larger systems that combine internal multitasking by teams with a multitasking process between teams; in the latter case, the goal to solve a complex problem becomes the search for alternatives to a prevailing situational interpretation, characterized by the collection of supporters and the persuasion of neutrals to conflicting interpretations (e.g., politics; see Fig. 5). When users

[20] *Wall Street Journal* (2012, 12/11), "Madoff Scandal Still Haunts Victims".

[21] As examples, the fight led by Democrats for national health care in 2010 was mirrored by the fight led by Republicans in 2012 to make the State of Michigan a 'right-to-work' State without union constraints on worker paychecks; *Wall Street Journal* (2010, 3/9), "Why Obama Can't Move the Health-Care Numbers. For every voter who strongly favors the plan, two are strongly opposed." And *The Examiner* (2012, 12/10), "Dems in all-out fight for union power in Michigan".

[22] Donnelly, J.M. (2012, 9/28), "Medical mergers pick up. Independent community hospitals face extinction", *Boston Business Journal*: "As the Massachusetts hospital merger madness intensifies, the independent community hospital is becoming an endangered species. ... Going it alone is becoming an increasingly uphill battle. Impending Medicare cuts threaten thin margins at community hospitals, new pay-for-performance insurer contracts require expensive health IT systems to monitor quality, and emerging Accountable Care Organizations require both academic medical centers and community hospitals to work together to coordinate the best care at the lowest price."

expect one-sided solutions to a problem and get a convergence to it (as in data fusion), trust should increase; but under uncertainty when users expect a two-sided discussion of competing choices, a process that considers the implications of alternative views should produce more trust (Lawless et al., 2010).

Why is interdependence so difficult to understand?

The great social psychologist Jones (1990) concluded that the human interaction could never be understood. It is natural to want to disagree with him; among others, Harris (2010) believes that a single truth for human behavior is not only desirable but also possible. However, the interdependence between action and observation makes intuition fail at the human level as claimed by Bohr (1955) just as it does at the atomic level (Gershenfeld, 2000).

The ultimate goal of human decision-making is unknown, but has been attributed, among other possibilities, to reason (Aristotle), religion, exploration, reducing suffering and death, and improving the human condition. Sen (2000) concluded that democracy, rule of law, and checks and balances best improve social welfare. Checks and balances imply the long-postulated value of the struggle for truth.[23] We have found, for example, that a higher U.N. HDI (human development index) is associated with indices reflecting more freedom ($r=.74$, $p<.01$), less inequality ($r=.60$, $p<.05$; i.e., Gini index), and a cleaner environment ($r=.72$, $p<.01$). A lower interest rate on 10-year sovereign bonds is associated with more freedom ($r=.58$, $p<.05$) and a nation's competitiveness ($r=-0.85$, $p<.01$).[24] But governments without checks and balances, like China, are often unable to reduce corruption.[25] In the solution of difficult problems under uncertainty, if the goal of decisions is to help individuals in a group and the group to survive, we and others have concluded that they are improved when the best decisions overcome public struggle, checks and balances are present, and free speech and markets exist (e.g., Justice Holmes, 1919; Justice Ginsburg, 2011; for Ginsburg, see Washington Post[26] and Miller, 2012). We hypothesize that better decisions with fewer mistakes arise after the available information is processed, reducing uncertainty.

Why is new theory necessary?

Single-user robots are rapidly increasing in number. Nanobot robots are being used to fight cancer; robots are being used to help amputees and babies overcome mobility problems;

[23] In philosophy, where "inquiry is a 'struggle' to replace doubt with 'settled belief', see Pragmatism; in theological struggles for truth, see Free Will; *Stanford Encyclopedia of Philosophy* (plato.stanford.edu).

[24] The USA is ranked 19th in the Economist's Democracy Index 2011; China is ranked 141st (https://www.eiu.com). The USA is ranked 10th in the 2012 Index of Economic Freedom by the Heritage Foundation, China 138th (http://www.heritage.org/index/); the USA is ranked 7th in the World Economic Forum's Competitiveness Index, China 29th (http://www.weforum.org).

[25] *The New York Times* (2012, 10/25), "Hidden Riches for Family of Chinese Leader." From the article about the immense wealth accumulated by Wen Jiabao's family: "In the winter of 2007, just before he began his second term as prime minister, Wen Jiabao called for new measures to fight corruption, particularly among high-ranking officials. "Leaders at all levels of government should take the lead in the anti-graft drive," he told a gathering of high-level party members in Beijing. "They should strictly ensure that their family members, friends and close subordinates do not abuse government influence.""

[26] Per Justice Ginsburg in the *Washington Post* (2011, 6/20), "High court throws out states' climate lawsuit"; "… as with other questions of national or international policy, informed assessment of competing interests is required,"

etc.[27] Robotic logistics and warehouses are in operation.[28] In September 2012, California became the second State (after Nevada) to license "driver-less" cars on its State highways.[29] The *Wall Street Journal* recently wrote a favorable article on driverless cars, underscoring a more rational approach with annual savings from the reduction of costs, time wasted in highway "grid-lock", and number of lives lost.[30] Already involved in illegal drug arrests, border patrol, and disaster relief, drones are expected to number 30,000 or more unmanned aircraft flying over the USA by 2030.[31] Overall, there will be numerous robots, all made by different companies, operating in the home,[32] driving on the road, teaching and working in hospitals, industry and businesses.[33] But to continue to expand and, more importantly, work as teammates with humans and other robots, users will want to be assured that autonomous robots can work with each other and humans and autonomous machines as part of hybrid teams that they and the public can trust (Lee & See, 2004), even under uncertainty.

Teams are important to business, the military, sports and society. In medicine, from the VA National Center for Patient Safety, its "MTT [Medical Team Training] has produced sustained improvement in OR [Operating Room] team functions, including decreased delays and improved case scores" (Wolf, Way & Stewart, 2010). However, team performance is "fraught with confusion" (Bell et al., 2012), especially in medicine: "The medical field lacks a theoretical model of team performance to improve patient safety."[34] But as resources to health care providers decrease,[35] approaches that rely on teamwork and multitasking become more important.[36] With our theory, we aim eventually to develop metrics for hybrid team performance.

Current work

Trust. Trust is a key issue in the development and implementation of autonomous systems working with and for humans. Humans must be able to trust the actions of the autonomous machines to want to work with them, and autonomous machines must be able to develop or establish trust in the actions of human co-workers. This trust between and among hybrid agents must be extended in a manner that ensures efficient and effective communication, collaboration and the free flow of information while minimizing the information barriers between robots, machines and humans (Conant, 1976).

---

[27] 2012: see the review by IEEE at http://spectrum.ieee.org/robotics/medical-robots

[28] *CNET* (2012, 3/20), "The robots are coming! Better get used to it."

[29] *AP* (2012, 9/25), "California Governor signs driverless cars bill."

[30] *Wall Street Journal* (2012, 9/24), "Who's behind the wheel? Nobody. The driverless car is coming. And we all should be glad ..."

[31] *The Plain Dealer* (2012, 7/28), "Unmanned aerial drones are coming, worrying privacy advocates".

[32] Gates, Bill (2006), "A robot in every home", *Scientific American*.

[33] *Wall Street Journal* (2013, 1/8), "Jenkins: Robots to the Rescue? The flip side of an entitlements crisis is a labor shortage".

[34] U.S. Department of Healthcare & Human Services, Agency for Healthcare Research and Quality, "Chapter 5. Conclusions and Recommendations", retrieved 3/11/12 from www.ahrq.gov/qual/medteam/medteam5.htm .

[35] Health care providers are believed by some health care providers to be forcibly shifting from seeking cures to palliative care and euthanasia to contain costs (*Wall Street Journal*, 2012, 3/16, "Notable & Quotable, Dr. Jeffrey A. Singer on the medical profession's move from the Hippocratic oath toward the "veterinary" ethic.").

[36] As an example of a medical team, accountable care organizations (ACOs) are increasing in response to the economic rules in the new health-care law, where an ACO is a collective of "medical care providers who band together under one business umbrella" to reduce costs and increase profits. *New York Times* (2012, 3/12), "Small-picture approach flips medical economics".

Trust can mean different things in different contexts. For flight control systems on airplanes, trust may mean meeting rigorous criteria regarding the structural qualities of an airplane, flight worthiness, and control system stability. In the context of an autonomous automobile safely carrying passengers, trust in the system may be the expectation that the autonomous robot will respond correctly not only to foreseen road and traffic conditions, but also to unusual circumstances (e.g., gridlock; alternative route planning; a child running into the street while chasing a ball; running out of gas on the highway; an engine catching fire; hearing and seeing an approaching ambulance or fire engine with siren blaring; or a flat tire causing the vehicle to swerve unexpectedly).

In the context where multi-tasking occurs with hybrid teams, trust may more closely relate to the management of the interdependence among teammates in correctly sensing, reading and interpreting each other's voice commands, gestures and observed actions to increase the likelihood that hybrid teammates act as expected of each other. System controllers, human or machine, must be able to control at the individual, group and system levels; and society must be willing to entrust its citizens, including the elderly and young, to a multi-tasking hybrid system composed of autonomous agents and humans working together. However, the dynamic control of interdependent teams has not yet been solved (Jamshidi, 2009). But when it is solved, as sensory technology evolves, we expect to find that bidirectional trust becomes interdependent between sentient agents, each capable of reacting to another's actions in hybrid teams, systems and society.

When does trust arise? In a single agent or system composed of independent agents, trust occurs when an agent, including humans, is performing satisfactorily over a range or set of behaviors, from the maximum of underperformance (infimum) to the minimum of over-performance (supremum), a range governed by (emotional) set-points (from Diener, 1984; Lawless et al., 2007). The entropy, *S*, increases as the points in the set become equiprobable to $p = 1/n$, giving $S = \log n$. Thus, based on Shannon's information theory, competitive systems, composed of independent players, generate more information than cooperative systems, where one agent is dependent on another. But for interdependent agents, we expect Shannon's theory of information to be replaced with Von Neumann's, a different result (Gershenfeld, 2000): Under competitive situations among sentient agents, alternative viewpoints arise spontaneously under uncertainty to form a superposition of both in the minds of the undecided (e.g., Google's Android Smartphone versus Apple's iPhone as both compete for undecided customers; for more, see the illustration in Fig. 2 and Fig. 5).

When alternative viewpoints about reality arise, what has trust to do with multi-robot or hybrid systems? For a multi-tasking human group or firm seeking to increase its competitiveness to gain an advantage for clients with an approach that reduces entropy (for knowledge, $S = 0$; in Conant, 1976), for example, if an algorithm can be used to predict excellence in the medical choices that are made, it will increase trust and value in the services provided by that team:

> So Mr. Michelson built a series of proprietary algorithms to distinguish "the few who are the very best" from "the many who are very good," based on "the factors that predict excellence." For example, the premier caregivers for metastatic cancer are usually academic researchers on the cutting edge, not general oncologists. The best orthopedic surgeons perform many procedures as they master the clinical learning curve, ideally for a single injury.[37]

[37] *Wall Street Journal* (2012, 9/21), "Leslie Michelson: Doctor to the 1% (and Maybe Someday to You)"

In this example, Michelson's goal was to ensure an accurate diagnosis and lay out all the treatment options with alternative viewpoints. Thus, his Private Health firm functions as a kind of running, independent second-opinion. It operates in the twilight zone under uncertainty where there isn't a "best practice" for when and how to treat, but a continuum of tradeoffs between risks and benefits that vary from patient to patient.

Providing intelligent second opinions raises an important issue with advanced robots working interdependently with humans. As stated earlier, human teams work together to solve two broad classes of problems: those previously solved problems that require cooperation to increase efficiency, consuming the information already available with existing algorithms, laws, or procedures that reduce uncertainty and increase stability; and those unsolved or intractable problems that require competition, generating new information to solve a problem, but increasing uncertainty, instability and disruption in the process. The latter is characterized by the competition between alternative viewpoints.

The Data Fusion Problem. To decide on the path forward, hybrid multi-agent teams and systems need to aggregate or "fuse" data across its group, initially at a central location (Cummings et al., 2011). But whether centralized or decentralized, data fusion is the classic duality between perception and action first noted by Bohr (1955); fusion aggregates overlapping information into a single basis state with state estimation functions to complete a situational context for an autonomous hybrid team, triggering a decision on resource management (e.g., Steinberg et al., 1999). But, confronted by uncertainty with perceptions of incompleteness, humans confabulate[38] while machines interpolate or extrapolate. Subject matter experts, including physicians and pharmacists,[39] make mistakes based on their interpretations (Tetlock, 2010; Tversky, in Shafir & LeBoeuf, 2002). The result may be a computational convergence to a solution that is not rational and puts a group's survival at risk.

The fusion process (Waltz and Llinas, 1990) attempts to correct this flaw with feedback, but confirmation bias (Darley et al., 2000) makes the convergence to a decision difficult to challenge or overturn, making illusion more likely, figuring directly into accidents caused by the humans who are guided by machines and robots (Smallman, 2012): Emotional convergence caused the USS Vincennes in 1988 to shoot down an Iranian commercial airliner, killing all aboard; command convergence suppressed warnings by the submarine crew to its Commander against a rapid ascent, causing the USS Greenville tragedy in 2001 that broke apart and sunk a Japanese tour boat; and relaxation convergence after a long deployment in 2009 led the submarine crew to sleep at their duty stations and the Commander and navigator to be absent from the Bridge, causing the USS Hartford to collide with the USS New Orleans. In these three incidents, the machine (computers) had the correct solutions, but were either ignored or disregarded by human users.

But, based on prior research and field experience (Cummings et al., 2010), we also expect to find model imperfections in automation systems; that is, machines can be wrong, too. Air France 447, an airbus flying from Brazil to Paris in 2009, provides an example of automation

[38] Interview of the neuropsychologist, Dr. Michael S. Gazzaniga; in *New York Times* (2011, 10/31), "Decoding the Brain's Cacophony"

[39] "Since 1992, the FDA has received nearly 30,000 [voluntary] reports of medication errors" indicating that new technology may reduce the confusion among drug names and labeling errors, while monitoring expected patient responses to medication (In the FDA's 2011 "Strategies to Reduce Medication Errors: Working to Improve Medication Safety"; www.fda.gov/Drugs).

bias,[40] initiated by faulty sensor data. After its pitot tubes froze in turbulent weather at night, indicating a loss of airspeed, multiple alarms confused the co-pilots. The plane's flight director, which relies on sensory information from the pitots to guide a plane, gave out faulty, conflicting information. The co-pilot nosed the plane upward, thinking he was going too fast, stalling and crashing the airliner, killing all aboard. From BEA chief Jean-Paul Troadec,[41] "the pilots should have turned off automatic signal systems and flown entirely manually as soon as they realized the pitots were blocked."

Alternative Viewpoints. Smallman (2012) agrees that convergences can be challenged with alternative viewpoints. His system tracks and visually displays the agreement and disagreement among users across a narrow system (e.g., submarine). However, no known method exists to compute alternative viewpoints. But by constructing orthogonal pro-con vectors during the sensory fusion process, a tool to find and display alternative viewpoints could mitigate mistakes in the control of hybrid systems (Lawless et al., 2011); as another example of the trouble with single-mindedness, approved by Marine Officers in Helmand in Afghanistan despite a warning not to fire that did not get transmitted and was retracted by Air Force analysts in Indiana but not shared with the controllers or Officers, a Predator controlled by an Air Force crew in Nevada killed a Marine and Navy medic in a fire fight in 2011.[42]

We hope to build on Smallman's (2012) work to mitigate convergence processes with (medical and other) team decision-making. The standard JDL fusion model also uses convergence processes; e.g., Llinas et al. (2004) highlight the value of belief consistency (p. 6) to build a "community consensus" (p. 13). But alternative beliefs are permitted in the JDL Fusion model (Steinberg et al., 1999). Thus, working with Smallman to replace his non-computational approach with a mathematical model based on orthogonal beliefs advances the science of fusion and decision-making.

As the first of two examples in the improvement of decisions for humans, although numerous claims had been made by the Department of Energy (DOE) that it was protecting the environment before 1983, the self-regulated DOE had already grossly contaminated its nuclear weapons complex (1940s-1980s) with a cleanup cost estimated today in the hundreds of billions (Lawless et al., 2010). In contrast, today, under the checks and balances afforded by competing scientific and engineering organizations, regulators and citizens, DOE has made significant strides in its cleanup.[43]

As the second example "Hospitals without intensivists can still achieve significant reductions in mortality in their ICUs by implementing a multidisciplinary, team-based approach," said the study's lead author, Kahn.[44] "Patient outcomes are improved when physicians, nurses, respiratory therapists, clinical pharmacists and other staff members work together to provide critical care as a team" (for details, see Kim et al., 2010). This finding increases the motivation to find a theory of teams that is valid (Bell et al., 2012).

---

[40] Automation bias is "the tendency to disregard or not search for contradictory information in light of a computer-generated solution that is accepted as correct …" (Cummings, 2004).

[41] *Washington Post* (2012, 7/5), "Investigators outline key moments during Air France Flight 447's fatal 2009 journey"

[42] *Los Angeles Times* (2011, 10/14), "U.S. deaths in drone strike due to miscommunication, report says"

[43] Today, for example, different aspects of DOE's operations at its Savannah River Site (SRS) are overseen at the national level by the Nuclear Regulatory Commission (NRC); Environmental Protection Agency (EPA); Defense Nuclear Facilities Safety Board (DNFSB); and the National Academy of Sciences (NAS); at the State level by SC's Department of Health and Environmental Control (DHEC); and by the SRS Citizens Advisory Board (SRS CAB).

[44] Quotations of Kahn from http://www.uphs.upenn.edu/n

In sum, better decisions arise when the available information is processed to reduce uncertainty. Fusion processes that simply aggregate data are unlikely to reduce errors whenever competing viewpoints exist but remain unexpressed.

Theory (see mathematical appendix)

Overview. Initially, we limit our computational model to teams and firms. From there we build up to systems. Likely a cause of the present difficulties with teams (Bell et al., 2012) and organizations (Pfeffer & Fong, 2005), in the traditional approach to systems, conventional theory is subjective; e.g., known as "critical systems thinking", Ulrich (2002) constructs a process to seek consensus on what constitutes a social fact without regard to social reality. At the other extreme, the new discipline of network science not only focuses on behavior, it purposively disregards subjective information (Barabasi, 2012). In contrast, we include both physical and social behaviors, but also the perceptions and illusions central to decision-making processes. As part of this paper, we extend our model to social modeling to include debate and social evolution (e.g., what are the impediments to innovation?).

Single (human) agents multi-task poorly (Wickens, 1992). Multi-tasking is the function of groups (Ambrose, 2001), like a firm, baseball team or team of decision makers (e.g., multi-robot teams). A team creates a state of interdependence among its agents (Smith & Tushman, 2005). But action and observation derive from independent brain systems (Rees et al., 1997). Because human attention occurs at each moment in time at a single point of focus (Anderson, 2004), action and observation are forced to interact interdependently in a series of tradeoffs (Lawless et al., 2011), which we illustrate with a simple bistable illusion (Fig. 1). Underscoring the problem with "understanding" and "meaning" in social reality, bistable shifts between action and sensory channels, or between incommensurable beliefs or interpretations, cannot be held in awareness simultaneously (Cacioppo et el., 1996).[45] The Necker cube illusion below illustrates that two incommensurable interpretations can derive from a single database.

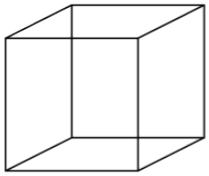

Figure 1. Necker cube illusion. It has two mutually exclusive interpretations, a cube pointing downward and to the left, or a cube pointing upward and to the right. One image of the Necker cube could represent, for example, belief in the value of Apple products, the other Google products; different religions; or different political positions. Viewing both interpretations simultaneously is not possible (Cacioppo et al., 1996).

Human memory does not react solely to sensory information, but also Gestalt groupings and experiences (Adelson, 2000), implying that uncertainty from interpretation is greater than or equal to the uncertainty from sensory information (i.e., signal detection theory, SDT, governs the

[45] *New York Times* (2012, 9/28), "Why the Beaver Should Thank the Wolf" ... Stands of aspen and other native vegetation, once decimated by overgrazing, are now growing up along the banks. This may have something to do with changing fire patterns, but it is also probably because elk and other browsing animals behave differently when wolves are around. Instead of eating greenery down to the soil, they take a bite or two, look up to check for threats, and keep moving. The greenery can grow tall enough to reproduce."

transmission of information between agents). When uncertainty among different viewpoints is low, eigenvalues for matrices representing two different communities commute, $[A,B]=0$; e.g., strong leader and weak followers; dictators; autocratic military command and control; and 6-sigma firms. In this case, convergence processes reduce the usable information available (e.g., confirmation bias; also, one-sided interpretations of situational awareness often imply incompleteness or confabulation), reducing evolution and innovation (e.g., Christensen, 2011: the challenge of managing disruptive technology by a large firm may account for why GE has become less of an innovator).

In contrast, unlike commuting matrices, when problem sets are intractable or operate in uncertain environments, we have concluded that competition among different worldviews best serves public welfare (i.e., a "gap" in the estimation of social reality exists, implying that $[A,B]=iC$; e.g., Smallman, 2012). We propose that interdependence creates a superposition of Gaussian states, where ψ is the standard state vector and *a* and *b* are bistable probabilities over the range [0,1]. Then vector ψ for an improved metric of robustness becomes:[46]

$$|\psi>= a\,|action> + b\,|observation>, \qquad (1)$$

and $|a|**2$ is the probability of being in state *a* when measured (e.g., human training with mobile robots decreases skill uncertainty while inversely increasing observation uncertainty; from Lawless et al., 2011). Equation (1) reflects a 90 degree rotation from |*action*> with probability $|a|**2$ to $|observation>$ with probability $|b|**2$. Illustrated in Fig. 2, this gap in social reality is less likely to exist in the minds of those who are convinced in the rightness of their interpretation of reality, nor its alternative interpretation in the minds of their opponents, rather it exists when considering both views simultaneously in the minds of the undecided, or neutrals, as a superposition of both perspectives (Lawless et al., 2010):

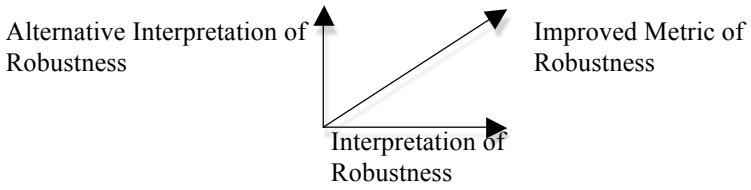

Figure 2. An application of Equation (1) becomes $|\psi>$ = *a*|*RI interpretation*> + *b*|*RI alternative interpretation*>. When robustness is uncertain and open to interpretation, we expect to find that its interpretation and its best alternative interpretation are orthogonal, leading us to ψ, an improved, weighted metric for robustness.

Substituting for equation (1), at the macro signal level, Cohen (1995) has shown that non-commutative operators (i.e., $[A,B]=iC$) can be converted into Gaussian distributions that form Fourier pairs (with sigma as the standard deviation, *t* as time and *f* as frequency; note that *t* and *f* are orthogonal). That is, ψ becomes:

$$\sigma_t \sigma_F \geq 1/2. \qquad (2)$$

[46] As a reminder, the brief tutorial in the appendix provides a review of the mathematics, especially equations (1) and (2), as well as the concept of "gaps".

Skills convergence in a Gaussian distribution implies tradeoffs between Fourier pairs. From Cohen (1995) on signal theory, a "narrow waveform yields a wide spectrum, and a wide waveform yields a narrow spectrum and that both the time waveform and frequency spectrum cannot be made arbitrarily small simultaneously." (p. 45); e.g., based on suicide bombings in Jerusalem, the pattern "is always a tradeoff between model accuracy and area reduction that we can describe for any given model" (Willis, 2007).

Existing models. Game theory was one of the first mathematical models of interdependence (Von Neumann & Morgenstern, 1953), but it has numerous problems: interdependence is static (the "dynamics" of repeated games simulate that in the movies); the values in game choices are arbitrary; and, consequently, games have not been validated (Schweitzer et al., 2009). On values, Axelrod (1984, pp. 7-8) concluded that competition reduced social welfare: "the pursuit of self-interest by each [participant] leads to a poor outcome for all". This outcome can be avoided, he argued, when sufficient punishment exists to discourage competition. We agree with Axelrod for teammates and members of firms; however, cooperation between competitors, like Apple and Google, is collusion. Further, Arrow (1968) established that competition was Pareto efficient or optimal (with constraints). Game theory not only does not account for the innovation that arises from the competition between groups, but also, neither does it account for the illusions and deceptions that confer a competitive advantage to users, yet reactance to the discovery of deception and illusion are central to social dynamics (e.g., "wolf in sheep's clothing"). Deception creates the illusion of low risk, e.g., Greece in 2010; Madoff in 2009; and Enron in 2001.

What is needed for hybrid or pure robot teams is a transactions or dynamic exchange model that tracks bidirectional sensory effects and interdependent uncertainty where sensors are used to dynamically update the parameters of a model (like the sensors that continuously update the National Weather Service forecast model). Specifically, the transaction costs of individuals inside of a firm are lower than they would be by the same individuals acting outside of the firm (Coase, 1937). The end result should be collective control theory; e.g., the waggle dances performed by interdependent bees exemplify the exchanges known as quorum sensing (Sasaki & Pratt, 2011).

Ongoing Research

Information gaps. To display uncertainty "gaps" in data fusion processes and to improve decisions under uncertainty (Lawless et al., 2011) by reducing confirmation bias and other convergence processes (Steinberg et al., 1999), we are pursuing a mathematical study of differential clustering between alternative views (Smallman, 2012). The result for an improved metric is to let data fusion arrive at its interpretation of robustness while using the same data to find the best alternative interpretation (see Figures 1 and 2 above).

We plan to use Repast and other Java toolkits for Agent-Based Modeling (ABM) to develop models of a team, two teams competing with each other, and two teams with an audience judging a team's robustness to model the competing viewpoints illustrated in the figure above.

Constructing a model of a team. Let each agent in a team represent a Gaussian distribution with its own interdependent Fourier pair: as multitasking skills increase (its uncertainty distribution narrows), observational skills decrease (its coupled uncertainty

distribution broadens); e.g., often, a child's tradeoffs during development emphasize either observation or motor skills, evolving, say, into a writer or an athlete. Let the (baseball) diamond in Fig. 3 below represent an interdisciplinary team, with agents at each interaction point, and the legs representing the channels of bidirectional information flow between the multi-tasking agents. As uncertainty in the multitasking skills decrease on a leg between two team members, it becomes zero in the limit as cooperation increases to a maximum: $[A,B] \rightarrow 0$ (e.g., 6 sigma).

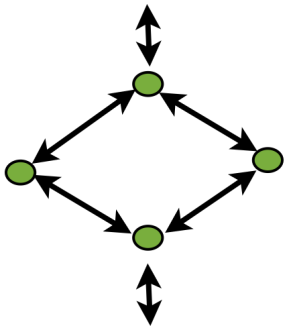

Fig. 3: Bistable information flows in from the bottom and out the top of the group structure; the information is distributed in channels among the four agents who create a state of multitasking across the team; however, skills uncertainty and observational uncertainty are interdependent, making them inversely related.

From equation (1), $a \rightarrow 1$ as the uncertainty in multitasking skills goes to zero. But when that happens, from equation (2), the standard deviation for observations goes to infinity, producing noise ($b \rightarrow 0$).

Evidence

Interdependent uncertainty generates tradeoffs. As uncertainty in an agent's skills decrease, uncertainty in its observations increase:

Individuals: First, Tversky (Shafir & LeBoeff, 2002) found that an individual's justification for an action is unrelated to the action performed. Second, despite the supposed adherence by women who reported taking HIV prevention pills 95% of the time, the measure of effective drug levels in their blood near the time of infection was less than 26%.[47] Third, Lawless et al. (2010) found no association between book knowledge of air combat skills and performance in combat, but a significant association between training and performance. Fourth, in a 30-year meta-analysis, self-esteem was found to be unrelated to academic or work achievement (Baumeister et al., 2005).

Organizations: Fifth, Bloom et al. (2009) found that the estimation by managers of their firm's performance was unrelated to their firm's actual performance. Sixth, uncertainty in the observations of better-run organizations was found to become noise (e.g., the Mara Salvatrucha or MS-13 gang expends its free energy to become dark on purpose; Apple is dark by its successful teamwork; in Lawless et al., 2011). Seventh, game preferences made before games

[47] News, 2012, *Science*, 335: 1291.

played by humans were found to be unrelated to their game choices made during games (Kelley, 1992).

Finally, as simple examples: Many great golfers use swing coaches; many successful firms use consultants; and military team sorties end after the lead pilot debriefs the team. And even though there are no satisfactory theories of team performance (Bell et al., 2012), it has been found that team performance in aviation is improved with practice (Salas et al., 2008). Similarly, the Institute of Medicine concluded that following the example set by aviation with team training reduces errors in medicine (Kohn et al., 2000).

In sum, as Galton discovered when a crowd of individuals was able to accurately estimate the weight of an ox, groups that process all of the available information possible are more likely than individuals to be incorrect.[48]

The model of the firm as a machine--Energy in, entropy out. Organizational Dynamics

Survival depends on collecting sources of energy to offset entropy losses from disorganization, mistakes and wasted effort; i.e., $-\Delta A = \Delta E - T\Delta S$, where $dS = d_e S + d_i S$, ΔA is available energy, E, and dS is composed of external or "negentropy" and internal entropy. Many processes reduce the available energy by increasing entropy, like mistakes; e.g., despite lots of funds, the Department of Energy (DOE) Hanford's consensus-seeking citizen advisor board has slowed nuclear waste cleanup at the Hanford site compared to DOE's Savannah River Site's (SRS) majority ruled board which has accelerated cleanup at SRS (Lawless et al., 2010); and the European Union has rejected the minority control inherent in consensus seeking in favor of modified majority rule (WP, 2001). But what is the difference between majority and consensus rule and quorum sensing? It seems that quorum sensing for a colony of ants is based on reaching a tipping point (Sasaki & Pratt, 2011), making it similar to majority rule. Regardless, a successful organization collects excess ΔA (Coase, 1937) that becomes the glue for an organization's structure, increasing the need for boundary maintenance across a team, organization or social structure. The barriers around a firm that form its boundary serve to prevent external noise from entering into the information channels that agents construct around a firm to better be able to communicate with each other.

An organization's incoming negentropy (S_e) derived from say sales must be greater than S_i, its losses (e.g., its production wastes, profit misallocation, social wastes) and its overhead (e.g., its welfare costs, products generated, and boundary maintenance). To balance inputs and outputs, when $S_e > S_i$, a firm is established (Coase, 1937) that is able to assemble complex products by multitasking (Ambrose, 2001).

Sociology. As social uncertainty increases, bistable interpretations, a mixture of reality and illusions, spontaneously arise among agents. Reactance against illusions serves to drive social oscillations; e.g., volatility in stock markets, mobile phone churn, and divorce rates. Here, reactance becomes the seed to create new organizations (from IBM comes Apple, MS). But how to model (e.g., illusions, debate, oscillations, resonance)?

[48] This idea is still current; e.g., Surowiecki's (2004) *The Wisdom of Crowds*, quoted Galton's story of the ox, p. XII; conversely, it is an effect that is lost under the combination of isolation and authoritarianism to produce stagnation, possibly reversing social evolution; see M. Ridley's review of the present dire straits of North Korea in "From Phoenicia to Hayek to the 'Cloud', in *Wall Street Journal* (2011, 9/11). Similar stagnation is seen in varying degrees in Cuba, Russia, and others, like Venezuela; e.g., *Bloomberg* (2013, 1/9), "Food Shortages in Venezuela Bigger Worry Than Constitution".

Social modeling. Moving from a group, where cooperation is imperative, to a more social setting where competing perspectives that form independent groups are likely, in Figure 4 below, we build on our model presented earlier in Figure 3.

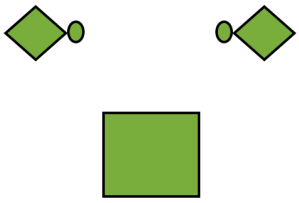

Fig 4: We plan to build on the model of a firm with computational agents to model a social debate that represents orthogonal viewpoints presented before a neutral audience (or to model the competition for customers between, say, Apple and Google). We envision that the team located at the upper left (from Fig. 3) is counter-balanced by a similar team (from Fig. 3) located at the upper right, with the square below representing the neutral observers in the audience. Further, we believe that springs can be used among the three groups to model the oscillations in the sources of information flow cycling among them (Mendelowitz et al., 2009).

A social model of competitive debates (e.g., in politics, courtrooms, science). In Fig. 4, let two speakers each represent independent organizations, with an audience of neutrals in front of both. To model debate (or competition), the two different views do not commute; i.e., $[A,B] = iC$; where i represents phase space, and C a gap in the Knowledge, K, of Reality, R, where K implies that S-> 0 in the limit. Social debate can be modeled with an inverted Prisoners Dilemma Game: D-D improves social welfare (competition), C-C reduces it (cooperation); i.e., successful debate increases social welfare (increasing social ΔA; further, the winning organization out-gains ΔA). Conjecture: Despite open conflict (increasing S), democracies solve problems better than autocracies; e.g., the autocratic self-rule rule in China, just like with DOE before 1983, under the rule of the Communist Party has led to China's grossly contaminated groundwater, air, and food supply.[49]

In Figure 5 below, real data provides an example of when community matrices do not commute (i.e., $[A,B] = iC$). In the competition for the presidency, Republicans and Democrats fight to get their orthogonal interpretation of reality accepted by neutrals in the public. Intersections between the curves represent limit cycles of orthogonal processes where neutrals adopt and reject interpretations to force information processing that continues until a clear winner emerges. However, based on equation (1), an undecided individual exists in a neutral state, holding both alternative views in a state of superposition until a decision is made.

[49] Fully 90% of its shallow groundwater is contaminated, in *Science* (2011, 11/11), "China to Spend Billions Cleaning Up Groundwater".

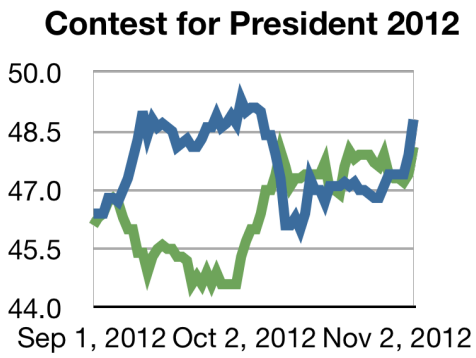

Fig. 5. Data from RCP (11/5/12).[50] If we divide the nonlinear chart into three regions, the widest divergence between Obama and Romney occurs in Region 1--in this region, there was little debate about who was leading the contest for President; nearly overlapping curves were found in Region 2--in this region, the debate about who was the leader was contested;[51] and the ending curves are in Region 3, indicating that Obama would win the race.[52]

Discussion

Western philosophy, social learning theory and brain science, among others such as computational social science, often address theoretical problems like robust intelligence by focusing on the individual, known as methodological individualism (MI). From Turchin's (2005, p. 11) criticism that "individual movement is determinant", MI is reductionist, yet it underpins game theory, modern economics and the law (Ahdieh, 2009). While MI remains fruitful, its approach to the study of interdependence is simplified. Applied to a team or firm to develop information say for social network analyses, a common approach is to solicit self-reported information from the individuals under study (e.g., Hanneman & Riddle, 2011); conversely, network science also focuses on the individual, but it rejects subjective information (see Barabasi, 2012). The subjective focus is on the convergence of "sense" data, exemplified by a wide consensus in morality and religion; the physical focus is on the convergence of "behavior" data, exemplified by Skinner's operant conditioning (rewards and punishment) and by data fusion practices. The primary benefit of MI is the construction of meaning to explain behavior,[53] social norms, self-interests and institutions (e.g., Axelrod, 1984). But the drawback is the loss of predictability (Taleb, 2012).

In contrast to MI, we believe that robust intelligence will not be either achievable nor efficient without including the effects of interdependence. Interdependence unites subjectivity and behavior (Bohr, 1955); opposing beliefs; and the elements of social interaction. Beginning with Adam Smith's (1776) "invisible hand", Cournot's (1838, p. 127) reactions among the parts

[50] http://www.realclearpolitics.com/epolls/2012/president/us/general_election_romney_vs_obama-1171.html
[51] For example, "Rove predicts Romney wins by 2% margin", *Real Clear Politics* (2012, 11/4).
[52] Real Clear Politics (RCP) collects and averages the polling results from Politico/GWU/Battleground, Rasmussen Reports, IBD/TIPP, CNN/Opinion Research, Gallup, ABC News/Washington Post, Monmouth/SurveyUSA/Braun, NBC News/Wall St. Jrnl, and Pew Research. See http://www.realclearpolitics.com/polls/
[53] For example, "… explaining how complex brain activity generates complex behavior." In Eliasmith, C. *et al.* (2012), p. 1202.

of a whole,[54] and game theory's (Von Neumann & Morgenstern, 1953) static configuration of the interdependent choices between two or more agents, the mathematics of social behavior has journeyed fitfully from the individual to the group. At a foundational level, the tension in the interdependent opposition from the "gap" in judging reality caused by mutually exclusive beliefs drives the dynamics of social conflict (Lawless et al., 2010). Even without a working mathematical model, Madison intuitively exploited interdependence with checks and balances to promote local instability in constructing a robust government, made stable when the self-interests collected around one point of view spontaneously balance those collected around its opposing point of view (Lawless et al., 2011). Over time, in the contests among ideas where one side gains an advantage characterized by the (stochastic) resonance of its beliefs among neutrals, causing the other side to fail or collapse, the winner becomes locked into its beliefs while the loser may turn (rotate) from the ideas that it had previously championed.[55] Open opposition is fundamental to social dynamics, social change and improvement in social welfare.[56] Thus does justice derive from the confrontation of opposing self-interests bearing on questions of innocence or guilt (Freer & Purdue, 1996); thus does a democratic legislature avoid the open conflict so common in 20th Century European politics (Schlesinger, 1949); and thus does science reduce mistakes by testing assumptions in peer-reviewed and open publications (e.g., Poincare, 1904-6).[57] The primary drawback from divergent, nonlinear processes is the loss of meaning.[58] But despite these divergences, the loss is offset by an increased ability to predict, albeit within limits, namely, by

[54] "… the economic system is a whole for which the parts are connected and react on each other …"

[55] Many examples from politics exist to illustrate the effects of belief rotation (turning) over time: Recently, Democrats under President Obama have strengthened their foreign policy credentials, leading to the following article about Republicans: "Can Republicans rediscover a once-celebrated policy tradition?" (2013, 1/3), *Washington Post*; as another, in 1864, the Democratic Party strongly opposed ratification of the 13th Amendment to the U.S. Constitution banning slavery (*New York Times* (2012, 11/29), "Steven Spielberg, Historian"); and, having lost the 2012 presidential election, Republicans have begun to revise their beliefs about immigration reform (*New York Times* (2012, 11/9) "Republicans Reconsider Positions on Immigration"). Similar effects occur with the success or failure of new technology; e.g., Apple's new iPad: "In pioneering a new category, it has in some ways been even more significant than the iPod and iPhone because it has disrupted so many different device manufacturers, creating a market opportunity for other smart phone makers, a challenge to other PC makers and even potentially influencing how we may watch television in the future in a multi-screen scenario. It has also extended digital content opportunities to make books and longer-form video on-the-go a more practical experience than they are on the Smartphone."(Ross Rubin, principal analyst at NPD Connected Intelligence; from NBC News (2012, March)"The iPad at 2: 'Huge impact' on our lives").

[56] A dictator gains minority (consensus) control by suppressing the information of opposition; e.g., from the *Wall Street Journal* (2013, 1/5), "Chinese journalists protest official censorship".

[57] Science is based on an adversarial process among scientists. However, the forensic evidence and testimony illustrates the concerns of scientists of insufficient training, scientific practices and certification of forensic science under the constraints of the courtroom (from NRC, 2009): "The [*Daubert versus Merrell Dow Pharmaceuticals, Inc., 1993*] Court expressed confidence in the adversarial system, noting that "[r]igorous cross-examination, presentation of contrary evidence, and careful instruction on the burden of proof are the traditional and appropriate means of attacking shaky but admissible evidence. (p. 10) … [But] there are important differences between the quest for truth in the courtroom and the quest for truth in the laboratory. Scientific conclusions are subject to perpetual revision. Law, on the other hand, must resolve disputes finally and quickly." (p. 12) However, "The adversarial process relating to the admission and exclusion of scientific evidence is not suited to the task of finding "scientific truth."" (p. 13) leaving the "current situation [with forensic science] … seriously wanting," (p. 13). To improve forensic science, the Academy recommended "a strong, independent, strategic, coherent, and well-funded federal program to support and oversee the forensic science disciplines" (p. 20).

[58] e.g., see opposing comments in an op-ed chastising President Obama, and an editorial supporting the President; the op-ed was by Samuelson, R. (2013, 1/1), "Obama's Leadership Failure*", Washington Post;* the editorial was by the *New York Times* (2012, 12/31), "A Tepid Fiscal Agreement".

building a system more robust to perturbations that is sufficient for control (Taleb, 2012, p. 136). For example, in politics, Madison foresaw that the tyranny of a majority is made unstable by increasing the number of factions that can form a majority (Madison's Federalist Paper No. 10; in Hamilton et al., 1945).[59]

Further, while MI draws attention to a firm's key individuals or leaders, the information collected is static. Mindful that energy is used to create order by building a firm's structures, which need to be replenished, repaired and replaced, the best structure for a firm minimizes energy consumption (i.e., with structure as an endogenous cost, including free energy, ΔA, given entropy information, S, the knowledge, K, used to build a structure occurs from processing information until $\partial S/\partial t \rightarrow 0$; interestingly, structural K occurs when $\partial E/\partial t \rightarrow \min S$, and a successful structural transformation occurs, as in a merger, when $\partial K/\partial t \rightarrow \min S$;[60] cf. Conant, 1976). From an exogenous perspective of a social engine that consumes large quantities of E to generate large amounts of S, the goal of a team or firm is to collect and store concentrated amounts of free E available (i.e., ΔA) to the organization in sufficient amounts for it and its members to survive by exceeding its structural generation of S on average.[61] But reversals of this equation can cause structures to collapse as a society becomes overextended financially, as it exceeds the carrying capacity of its environment, or when its free energy supplies diminish or end (Turchin, 2007; White, 2007), disrupting or breaking the structural ties that bind the society together. Writ small, the same can happen to firms; thus, mergers can occur when firms become vulnerable to a takeover,[62] or collapse outright.[63] Ironically, while E is used to build structures to better adapt to the environment, built structures reduce adaptability when the environment changes;[64] e.g., mergers that grow a firm's size reduce its volatility while also reducing its ability to adapt (Lawless et al., 2011). Per Taleb (2012, p. 101), as centralization increases, the "absence of fluctuations … causes hidden risks to accumulate", causing large mistakes.[65]

This discussion briefly summarized many of the key points in our paper. Information derived from self-reported or observed individual behavior is static; it cannot be used to reconstruct dynamic performance. But, we propose, these two information streams form interdependent and orthogonal axes. Interdependence not only characterizes a firm (Smith & Tushman, 2005), but also the glue that binds the parts of a firm together. Intuitively, attacking an organization produces characteristic information, like a sports team attacking an opponent in

[59] For a recent review, see the speech by G. Will, cited in Peggy Noonan's Blog (2012, 12/29), "The Most Important Speech So Far in the 21st Century?" *The Wall Street Journal*.

[60] *New York Times* (2008, 6/1), "Disney and Pixar: The Power of the Prenup". Quoting, "Most acquisitions, particularly in media, are value-destroying as opposed to value-creating, and that certainly has not turned out to be the case here," said David A. Price, author of a newly published book from Knopf, "The Pixar Touch: The Making of a Company."

[61] For a similar argument at the cellular level, see Ridley, M. (2012, 12/29), "Looking to a Lost City for the Origin of Life", *Wall Street Journal.* Importantly, social evolution also occurs with random exploration and stochastic resonance, hampered by the failure of past market leaders to transform themselves sufficiently to regain a leadership role; e.g., despite repeated efforts and a major marketing campaign, the new Microsoft tablet is failing to gain users (*Newsday*, 2012, 12/12, "Apple, Samsung battle for tablet market while Microsoft, Google, Amazon lag").

[62] e.g., the 2009 rescue of Chrysler by Fiat; see *New York Times* (2012, 1/9), "A Merger Once Scoffed At Bears Fruit in Detroit".

[63] e.g., Lehman Brothers Holdings, Inc. (former NYSE ticker symbol LEH), the global financial services firm, entered into bankruptcy in 2008; see *CNBC* (2008, 9/15),"Lehman Brothers Files For Bankruptcy, Scrambles to Sell Key Business".

[64] Once the most dominant personal computer firm, Microsoft, valued at $435 billion in 2000, fell to $135 billion in value by 2009; Bloomberg (2012, 10/1), "Google Passes Microsoft's Market Value as PC Loses to Web".

[65] See also the op-ed piece by Taleb, N.N. (2012, 12/23), "Stabilization won't save us", *New York Times*.

search of vulnerabilities that can be exploited;[66] but, attacks in the form of challenges to the prevailing interpretations of reality lead to better decisions by reducing the illusions that precede large mistakes. These probes for weaknesses, the observations of Cournot's "reactions" to perturbations, may be the only reliable means of determining the robustness of a firm: the less observable is a reaction to an attack, the more likely robust is the firm's intelligence (Lawless et al., 2011), a prediction with no parallel in methodological individualism.

But, we believe, the most compelling support for our idea of the social value of competing perspectives is that equation (1) and (2) both represent orthogonal information, as does the limit cycle with real data presented in Figure 5 (Benincà et al., 2009); obversely, the lack of orthogonality has long been an important tool that flags the information sought for retrieval (Van Rijsbergen, 1975). Orthogonal representations under uncertainty indicate that the information available by measuring only a single point of view is necessarily incomplete; that the information processed by competing sides is necessary groundwork for cases to be considered by the Supreme Court; and that alternative interpretations of reality may moderate or prevent accidents (Smallman, 2012). Our arguments support Adelson's finding that the interpretation of reality is governed by experience and culture, often independently of signals from reality. Finally, the Necker cube and many another illusion is sufficient proof that two incommensurable interpretations of a single data set are possible, and that when an individual, team or group is focused on a single interpretation--say liberal or conservative, religious or atheist, insider or outsider (Tajfel, 1970)--the other interpretation is excluded from consideration at that moment (Cacioppo et al. 1996). Adding in self-interest, it becomes clear why justice requires competing viewpoints supported by competing self-interests (Freer & Perdue, 1996).

Conclusion

MI studies the construction of meaning to explain behavior, morality and institutions. But with "meaning" comes the loss of predictability (Taleb, 2012). In contrast, the primary drawback from the study of interdependence is the loss of meaning (Lawless et al., 2011). But the loss is offset by an increased ability to predict, albeit within limits. Predicting a "black swan" is difficult (Taleb, 2007); but it is made more difficult in interdependent situations by the generation of incomplete information. Our ultimate goal is to develop a theory of dynamic interdependence to apply robust intelligence to not only transform human firms, but also for the control of hybrid teams.

Regarding predictability, by making a hybrid team, firm or system more robust (Taleb's "antifragile"), the control of the group becomes more likely. The direct control of interdependence remains difficult (Jamshidi, 2009); but, based on our arguments, desirability of direct control loses value in the face of the uncertainty that produces the information

[66] The large bet placed in 2012 by JPMorgan's Chief Investment Office exposed the bank's vulnerability to exploitation by outsiders, but being bidirectional information, later on to JPM's management, too: "The so-called London Whale, the nickname of the U.K.-based trader Bruno Iksil because his trading book was so large, made a wrong-way bet on credit derivatives that led to the company's single biggest trading loss and at one point wiped out as much as $51 billion in market value. At least a dozen state, federal and international bodies are investigating the trades. ... "We had 100 people who worked every day for 90 days to help the real problem--the risk--not the ongoing regulatory review, but the real problem, to get the risk down so we didn't have ongoing exposure," Dimon said. While some people "acted terribly," the bank now has the "best management team I've ever had in my entire life," he said. "You learn the good and the bad about people and that's invaluable to find out who those people are. Invaluable", said Dimon, CEO." Bloomberg (2013, 1/9), "Dimon Says JPMorgan Executives 'Acted Like Children' on loss."

incompleteness arising from polling only one perspective (confirmation bias; Darley & Paget, 2000). Instead, we believe that a hybrid team can be controlled directly like human teams, and indirectly by strengthening its skills sufficiently well-enough to solve ill-defined or intractable problems on its own, robustly, like those by the best human teams all the while minimizing mistakes (Taleb, 2012, p. 293). This outcome is reached under uncertainty by making a hybrid team justify its decisions among its members and observers, by working through the opposing viewpoints that occur spontaneously, and by challenging illusions (or assumptions) wherever they arise. From Fig. 5 (and Galton), the goal of a hybrid team or firm should be to improve its predictions by pooling predictions from as many sources as possible. We add to this conclusion and to Galton's finding about the ox by concluding that (orthogonal) challenges to the interpretation of reality process information, making it easier to aggregate at any one moment in time, but consequently producing limit cycles over time.

For autonomous agents, we have concluded that an agent's or a firm's focus on one point in time implies interdependent tradeoffs under uncertainty, reducing the ability to multitask while increasing the likelihood of information incompleteness. The purpose of autonomous teams is to multitask. Multitasking consumes the information available; but to evolve, a system needs more information, gotten by competition, and processed into a decision (or knowledge) by the drive to capture neutrals (Powell et al., 2005).[67] If we are successful in our project with the application of our ideas for a new theory and model of interdependence and translating these ideas into new computational models, the mathematics and modeling of teams will bring the reality of hybrid teams from the distant future into the nearer future. If our research is successful, a stronger connection will be made between hybrid human-machine-robot teams and robustness, fragility, and the costs to adapt and evolve that will contribute to the quantification and metrics of robustness (e.g., Walsh et al., submitted). If successful, we will demonstrate with computational agent-based models interdependent effects with increasing fidelity such as fight or flight from the presence of other computational agents.[68] If successful, our work will have application not only for metrics, but also for the improvement of autonomy in hybrid teams (e.g., Lawless, 2012).

Applying these findings to government agencies, institutions and businesses allows us to conclude that competition can reduce the mismanagement and corruption that arise from the self-rule designed to control and regulate resources. Comparing the Department of Energy's (DOE) past failures at the time when it was self-regulated with its present successes when its decisions must now survive challenges from other federal and State agencies and the public allows us to conclude that self-regulation leads to an abuse of institutional power; in DOE's case, it produced a legacy of wide-spread contamination across the USA that has yet to be rectified despite the billions of dollars spent annually to remediate the environment impacted by DOE's past practices. China, under the self-rule of its communist party, has also mismanaged its environment. Self-rule is similar to consensus rule, the control of a majority's access to a resource with minority rules; consensus rule diffuses responsibility, makes reaching concrete decisions more difficult, and significantly increases the opportunity for the mistakes that reduce social well-being. Without the competition afforded by checks and balances, government

[67] Powell et al. (2005) found that the biotech firms that developed products under 3-year contracts with choices of other firms within a cohesive central network of collaborations produced an inferior result that had to be offset by recruiting new skills and innovations from outside the core network.

[68] By determining the limits to the defection of team members, the Prisoner's Dilemma Game may be used as a crude measure of teamwork.

agencies like DOE in the past and governments like China today, are often unable to prevent corruption, despite their good intentions.[69] This result generalizes to businesses that become monopolies (and to gangs that monopolize a nation, territory or state; in Lawless et al., 2011). For example, Google recently offered a settlement to the European Commission which had reported: "The Commission considers at this stage that [Google's] practices could harm consumers by reducing choice and stifling innovation in the fields of specialized search services and online search advertising."[70] Regarding free energy, organizations like DOE as well as institutions, firms, teams and gangs need money to survive. For the self-ruled DOE before 1985, this had meant making false claims about its environmental stewardship to the US Congress during its requests for appropriations (Lawless, 1985), money that filtered down to DOE managers who in turn corrupted the practices of scientists and engineers by funding only the research in the field that would produce the proof needed to satisfy Congress. More recently, including outside agencies to compete against DOE's self-rule has had a positive effect; however, including the public, even when the public has been naïve, has loosened the restrictions that DOE management has placed on its own scientists and engineers, reducing the number of mistakes made over the past two decades since the public has become involved. As an example from a public meeting held in 2011, the State of South Carolina complained that DOE was unlikely to close two high-level radioactive waste tanks by 2012 as it had legally agreed, caused by an ongoing set of unresolved challenges made by NRC (Lawless, 2013).[71] However, once the public got involved, all agencies including NRC quickly agreed and the tanks were closed in what one official described as "…the fastest action I have witnessed by DOE-HQ in my many years of service with DOE." In general, competition improves social well-being by increasing choice and by reducing the opportunities for corruption. But, to best protect social welfare, no federal agency, financial institution or business should be allowed to self-regulate.[72]

Finally, free energy, *E,* turns out to be a productive approach to the study of social interdependence for the structures and dynamics of hybrid teams, firms and systems. Conflict consumes more free *E* than cooperation or consensus-seeking for both individuals (Hagoort et al., 2000) and groups (Lawless et al., 2011), motivating a wide range of human behavior: among many others, mergers (Andrade & Stafford, 1999), criminal behavior (Fletcher, 1998) and lobbying (Lowery, 2007); e.g., criminals expend free *E* to reduce the emissions of *S* (entropy) to remain dark to their detection by police and the vulnerable (Lawless et al., 2011), as do the businesses[73] and hospitals[74] that fail to disclose adverse information about their operations, but in

---

[69] *King & Wood Mallesons* (2013, 4/11), "Briefing Notes: "Interpretation on Certain Issues Concerning the Application of Law in the Handling of the Criminal Cases of Offering Bribes"; http://www.chinalawinsight.com/2013/04/articles/dispute-resolution/briefing-notes-interpretation-on-certain-issues-concerning-the-application-of-law-in-the-handling-of-the-criminal-cases-of-offering-bribes/

[70] EU (2013, 4/25), "Antitrust: Commission seeks feedback on commitments offered by Google to address competition concerns"; europa.eu/rapid/press-release_IP-13-371_en.doc

[71] While much has been made of the "turf battles" that arise between nearly equal centers of power (e.g., Light, 1988), the undamped oscillations they generate are noteworthy (May, 1973).

[72] The operations of other Federal agencies, like the CIA, simulate self-rule by being isolated in whole or part from public scrutiny; e.g., see Keller, B. (2013, 4/14), "Cowboys and Eggheads", nyt.com

[73] *Wall Street Journal* (2013, 1/11), "KFC's China Flap Holds Lessons for Investors." Quoting, "On Dec. 21, Yum told U.S. investors that a recent Chinese state media report on a government investigation of improper antibiotics use by its chicken suppliers was hurting its huge KFC business in China. The announcement sent Yum's struggling shares down further. … Yum alerted its U.S. shareholders at the end of November that it expected a 4% drop in its same-store sales in China in the fourth quarter—the first such decline since 2009. But in that Nov. 29 release—and

the process, social well-being suffers and social evolution stagnates. Innovation and technology can mitigate the loss of free *E* (White, 2007), motivating the development of both. Inversely, free *E* is not only necessary to survive, to make better decisions, and to improve social welfare, but also free *E* is necessary to innovate and to develop new technology.[75] However, working through competing perspectives leads to fewer disruptive mistakes. The opposite happens when competing perspectives are suppressed: During its debut, two of China's bullet trains collided, but the physical evidence was quickly buried and the accident covered up.[76] Democracies also make mistakes. But the point of a democracy is to uncover the causes of its mistakes, like criminality, in a way that transforms practices to become less disruptive, less costly, and more robust.[77] For the purposes of our research, democracies address their problems by challenging the illusions that spontaneously arise under uncertainty. Applied to robust intelligence for hybrid teams, firms and systems, as uncertainties increase in social situations (e.g., with war, alliances and mergers, politics, and deep space travel), the value in the computational management of and metrics for interdependent probabilities increases.

Acknowledgements. For the first author, this material is based upon work supported by, or in part by, the U. S. Army Research Laboratory and the U. S. Army Research Office under contract/grant number W911NF-10-1-0252.

References

Adelson, E. H. (2000). Lightness perceptions and lightness illusions. *The new cognitive sciences, 2nd Ed.* M. Gazzaniga. MIT Press.

Ahdieh, R. G. (2009). "Beyond individualism and economics." ssrn.com/abstract=1518836, retrieved 12/5/09.

Ambrose, S. H. (2001). "Paleolithic technology and human evolution." *Science* 291: 1748-1753.

Anderson, John R. (2004). Cognitive psychology and its implications (6th ed.). Worth. p. 519.

Andrade, G., & Stafford, E. (1999). Investigating the economic role of mergers (Working Paper 00-006). Cambridge, MA; Retrieved from http://ssrn.com/abstract=47264, Harvard.

Arrow, K. J. (1968). Economic Equilibrium. *International Encyclopedia of the Social Sciences 4: 376–88*. D. L. Sills. London and New York, Macmillan and the Free Press.

Axelrod, R. (1984). *The evolution of cooperation*. New York, Basic.

Barabasi, A.L. (2012), Network science: Understanding the internal organization of complex systems. Invited talk. AAAI Publications, *2012 AAAI Spring Symposium Series*, Stanford.

Baumeister, R. F., Campbell, J.D., Krueger, J.I., & Vohs, K.D. (2005, January). "Exploding the

in comments at an investor conference a week later—the company made no mention of Chinese consumer concerns, citing instead a wobbly economy and the difficulty of outperforming a strong quarter the year before."

[74] *Reuters* (2013, 1/11), "Patients rarely told about medication errors." Quoting: "Most medication mistakes did not harm patients, the researchers found, but those that did were more likely to happen in intensive care units (ICUs). And ICU patients and families were less likely to be told about errors than patients in other hospital units."

[75] "Corporate management can not unendingly reduce cost without at some point curtailing output or embodying new technologies through investment to sustain it." Remarks by Chairman Alan Greenspan (2002, 10/23), "Productivity", At the U.S. Department of Labor and American Enterprise Institute Conference, Washington, D.C.

[76] China "is a government that refuses to be held accountable for its decisions, and that admits no criticism when criticism might make the difference between bold vision and monstrous folly." cf. *New York Times* (2011, 7/28), "China's High-Speed Politics".

[77] For example, no modern democracy has experienced famine (Sen, 2000).

self-esteem myth." *Scientific American*.

Bell, B.S., Kozlowski, S.W.J. & Blawath, S. (2012, forthcoming), Team Learning: A Theoretical Integration and Review, in Steve W. J. Kozlowski (Ed.), *The Oxford Handbook of Organizational Psychology*, Volume 1, NY: Oxford Library of Psychology.

Benincà, E., Jöhnk, K.D., Heerkloss, R., & Huisman, J. (2009). "Coupled predator–prey oscillations in a chaotic food web." *Ecology Letters* **12(12)**: 1367–1378.

Bloom, N., Dorgan, S., Dowdy, J., & Van Reenen, J. (2007). "Management practice and productivity." *Quarterly Journal of Economics* **122(4)**: 1351-1408.

Bohr, N. (1955). Science and the unity of knowledge. *The unity of knowledge*. L. Leary. New York, Doubleday: 44-62.

Bowles, S. (2012). "Warriors, levelers, and the role of conflict in human evolution." *Science* 336: 876-879.

Bode, S., He, A.H., Soon, C.S., Trampel, R., Turner, R. & Haynes, J.R. (2011), Tracking the unconscious generation of free decisions using ultra-high field fMRI, *PLoS One*, 6(6): e21612.

Box, J.A. (1978, R.*A. Fisher: The life of a scientist*, New York: Wiley.

Cacioppo, J. T., Berntson, G.G., & Crites, S.L., Jr., Ed. (1996). Social neuroscience: Principles, psychophysiology, arousal and response. *Social Psychology Handbook of Basic Principles*. New York, Guilford.

Chandra, F.A., Buzi, G. & Doyle, J.C. (2011), "Glycolytic Oscillations and Limits on Robust Efficiency", *Science*, 333(6039): 187-192.

Chagnon, N.A. (2012), *Noble savages*. New York: Simon & Schuster.

Christensen, C.M. (2011), *The innovator's dilemma*, Harper Business Reprint.

Coase, R. (1937). The nature of the firm, *Economica* 4: 386.

Cohen, L. (1995). Time-frequency analysis: theory and applications, Prentice Hall.

Coleman, J. J. (2003). The benefits of campaign financing. *CATO Institute Briefing Papers*, www.cato.org/pubs/briefs/bp-084es.html. Washington.

Conant, R. C. (1976). "Laws of information which govern systems." *IEEE Transaction on Systems, Man, and Cybernetics* 6: 240-255.

Cooper, J. (2007), *Cognitive dissonance: 50 years of a classic theory*. London: Sage publications.

Cournot, A.A. (1838/1897), *The Mathematical Principles of the Theory of Wealth*, Nathaniel Bacon (Tr.), New York: A. M. Kelley, Chapter XI, p. 127 (cf. http://archive.org/stream/researchesintom00fishgoog#page/n140/mode/2up).

Cummings, Mary L. (2004), Automation bias in intelligent time-critical decisions, *AIA&A, Proceedings Third Intelligent Systems Conference*.

Cummings, Mary L., Bruni, Sylvain & Mitchell, Paul J. (2010), Human Supervisory Control Challenges in Network-Centric Ops, *Reviews of Human Factors and Ergonomics*, 6: 34-78.

Cummings, M. L., How, Jonathan P., Whitten, Andrew & Toupet, Olivier (2011), The Impact of Human–Automation Collaboration in Decentralized Multiple Unmanned Vehicle Control, *Proceedings of the IEEE*, 1-12.

Darley, John M. & Gross, Paget H. (2000), "A Hypothesis-Confirming Bias in Labeling Effects", in Stangor, Charles, *Stereotypes and prejudice*, Psychological Press, p. 212.

Darwin, C. (1973). *The descent of man*, New York, Appleton.

Diener, E. (1984), Subjective well-being, *Psychological Bulletin*, 95(3): 542-575.

Eliasmith, C. *et al.* (2012), A Large-Scale Model of the Functioning Brain, *Science* 338, 1202-5.

Festinger, L. (1985), *A theory of cognitive dissonance*, Stanford University Press: Stanford.

Fletcher, George P. (1998). *Basic Concepts of Criminal Law*. Oxford University Press.

Freer, R. D., & Perdue, W.C. (1996). *Civil procedure*. Cincinnati, Anderson.

Gazzaniga, M.S. (2011), *Who's in charge? Free will and the science of the brain*. New York; Ecco.

Gershenfeld, N. (2000). *The physics of information technology*. Cambridge, Cambridge U. Press.

Gluck, K. (2012) "Heuristics for Robustness and Trust in Integrated Human-Machine Decision Systems", 13.15.12.B0909, retrieved from sffp.asee.org/program_search?method=post.

Gluck, K. A., McNamara, J. M., Brighton, H., Dayan, P., Kareev, Y., Krause, J., Kurzban, R., Selten, R., Stevens, J. R., Voelkl, B., & Wimsatt, W. C. (2012). Robustness in a variable environment. In J. R. Stevens & P. Hammerstein (Eds.) Evolution and the Mechanisms of Decision Making (pp. 195-214). Strüngmann Forum Report, vol. 11, J. Lupp, series ed. Cambridge, MA: MIT Press.

Hagoort, P., Hald, L., Bastiaansen, M. & Petersson, K.M. (2004). "Integration of word meaning and world knowledge in language comprehension." *Science* **304**: 438-441.

Hamilton, A., Madison, J., & Jay, J. (1945). *The Federalist 1787-88*. New York, Heritage Press.

Hanneman, Robert A. & Riddle, Mark (2011). "Concepts and Measures for Basic Network Analysis". *The Sage Handbook of Social Network Analysis*. SAGE. pp. 346-347.

Harris, S. (2010). *The Moral Landscape: How Science Can Determine Human Values*. New York, Simon & Schuster.

Holmes, O. W. (1919). Dissent: Abrams v. United States.

Jamshidi, M. (2009, to appear). Control of system of systems. *Intelligent Control Systems with an introduction to System of Systems*. T. Nanayakkara, Sahin, F., & Jamshidi, M. (Eds.). London, UK, Taylor & Francis. V. 2 (Ch. 8).

Jones, E. E. (1990). *Interpersonal perception*. New York, Freeman.

Kahneman, D. (2011). *Thinking, fast and slow*. New York, MacMillan (Farrar, Straus & Giroux).

Kelley, H. H. (1992). "Lewin, situations, and interdependence." *Journal of Social Issues* **47**: 211-233.

Kenny, D. A., Kashy, D.A., & Bolger, N. (1998). Data analyses in social psychology. *Handbook of Social Psychology*. D. T. Gilbert, Fiske, S.T. & Lindzey, G. . Boston, MA, McGraw-Hill. 4th Ed., Vol. 1: pp. 233-65.

Kim, Michelle M.; Barnato, Amber E.; Angus, Derek C.; Fleisher, Lee F.; & Kahn, Jeremy M. (2012), The Effect of Multidisciplinary Care Teams on Intensive Care Unit Mortality, *Archives of Internal Medicine*;170(4):369-376.

Kohn L, Corrigan J, Donaldson M. (2000), *To err is human: building a safer health system*. Committee on Quality of Health Care in America. Washington, DC: Institutes of Medicine. National Academy Press.

Lawless, W. F., Bergman, M., Louçã, J., Kriegel, N.N. & Feltovich, N. (2007). "A quantum metric of organizational performance: Terrorism and counterterrorism." *Computational & Mathematical Organizational Theory* 13: 241-281.

Lawless, W. F. (1985). "Problems with military nuclear wastes." Bulletin of the Atomic Scientists **41(10)**: 38-42.

Lawless, W. F., Whitton, J., & Poppeliers, C. (2008). "Case studies from the UK and US of stakeholder decision-making on radioactive waste management." *Hazardous, Toxic, and Radioactive Waste Management* 12(2): 70-78.

Lawless, W. F., Rifkin, S., Sofge, D.A., Hobbs, S.H., Angjellari-Dajci, F., Chaudron, L. & Wood, J. (2010). "Conservation of Information: Reverse engineering dark social systems." *Structure and Dynamics* **4(2)**.

Lawless, W. F., Angjellari-Dajci, Fjorentina, Sofge, Donald A., Grayson, James, Sousa, José Luis & Rychly, Laura (2011): A New Approach to Organizations: Stability and

Transformation in Dark Social Networks, *Journal of Enterprise Transformation*, 1:4, 290-322.

Lawless, W.F. (2012), Incompleteness, uncertainty and autonomy: Intelligent systems, *Lecture Notes in Computer Science: Proceedings Computational Social Science Society of the Americas (CSSSA)*, Santa Fe (http://computationalsocialscience.org)

Lawless, W.F. (2013), Citizen Contributions to the Closure of High-Level Waste (HLW) Tanks 18 & 19 at the Department of Energy's (DOE) Savannah River Site (SRS), Proceedings, Waste Management 2013 Conference, February 24 – 28, 2013, Phoenix.

Light, D.W. (1988), Turf battles and the theory of professional dominance. *Research in the Sociology of Health Care*, 7: 203-25.

Lee, John D. & See, Katrina A. (2004), Trust in Automation: Designing for Appropriate Reliance, *Human Factors*, 46(1): 50–80.

Llinas, J., et al. (2004, July), "Revisiting the JDL Data Fusion Model II", *Proceedings International Conference on Information Fusion*, Stockholm, Sweden.

Lowery, D. (2007), Why Do Organized Interests Lobby? A Multi-Goal, Multi-Context Theory of Lobbying, *Polity*, 39**,** 29–54.

May, R. M. (1973/2001). *Stability and complexity in model ecosystems*. Princeton Univ. Press.

Mendelowitz, L., Verdugo, A. & Rand, R. (2009), "Dynamics of three coupled limit cycle oscillators with application to artificial intelligence", *Communications in Nonlinear Science and Numerical Simulation*, 14: 270-283.

Miller, C. E. "Climate change litigation in the wake of AEP v. Connecticut and AES v. Steadfast: Out to pasture, but not out of steam." *Golden Gate, University Environmental Law Journal* **5**: 343-375; p. 355.

NRC (2009), "STRENGTHENING FORENSIC SCIENCE IN THE UNITED STATES. A PATH FORWARD", National Research Council's Committee on Identifying the Needs of the Forensic Science Community, Washington, DC.

Pfeffer, J., & Fong, C.T. (2005). "Building organization theory from first principles." *Organization Science* 16: 372-388.

Poincaré, Henri (1904/6), "The Principles of Mathematical Physics", *The Foundations of Science (The Value of Science)*, New York: Science Press.

Powell, W.W., White, Douglas R., Koput, Kenneth W. & Owen-Smith, Jason (2005), Network Dynamics and Field Evolution: The Growth of Inter-organizational Collaboration in the Life Sciences. *American Journal of Sociology* 110(4):901-975.

Rees, G., Frackowiak, R., and Frith, C. (1997). "Two modulatory effects of attention that mediate object categorization in human cortex." *Science* 275: 835-838.

Salas, E., Diaz-Granados, D., Klein, C., Burke, C.S., Stagl, K.C., Goodwin, G.F. & Halpin, S.M. (2008), "Does Team Training Improve Team Performance? A Meta-Analysis", *Human Factors*, 50(6): 903-933.

Sasaki, T. & Pratt, Stephen C. (2011). "Emergence of group rationality from irrational individuals." *Behavioral Ecology* 22: 276-281.

Schlesinger, A. (1949). *The vital center*. Cambridge, MA, Riverside.

Schweitzer, F., Fagiolo, G., Sornette, D., Vega-Redondo, F., Vespignani, A., & White, D.R. (2009). "Economic networks: The new challenges." *Science* 325: 422-425.

Sen, A. (2000). Development as freedom, Knopf.

Shafir, E., & LeBoeuf, R.A. (2002). "Rationality." *Annual Review of Psychology* 53: 491-517.

Silver, N. (2012), *The signal and the noise. Why so many predictions fail—But some don't/The art and*

science of prediction. New York: Penguin.
Smallman, Harvey S., (2012),TAG (Team Assessment Grid): A Coordinating Representation for submarine contact management, SBIR Phase II Contract #: N00014-12-C-0389, ONR Command Decision Making 6.1-6.2 Program Review.
Smith, Adam (1776/1977), *An Inquiry into the Nature and Causes of the Wealth of Nations*. University Of Chicago Press.
Smith, W. K., & Tushman, M.L. (2005). "Managing strategic contradictions: A top management model for managing innovation streams." *Organizational Science* 16(5): 522-536.
Steinberg, A.N., Bowman, C.L. & White, F.E. (1999), Revisions to the JDL Data Fusion Model, in Sensor Fusion: Architectures, Algorithms, and Applications, *Proceedings SPIE*, (3719).
Stolley, P.D. (1991), American Journal of Epidemiology, 133: 416.
Surowiecki, J. (2004). *The Wisdom of Crowds: Why the Many Are Smarter Than the Few and How Collective Wisdom Shapes Business, Economies, Societies and Nations*, Little, Brown.
Tajfel, H. (1970). "Experiments in intergroup discrimination." *Scientific American* **223(2)**: 96-102.
Taleb, Nassim Nicholas (2007), *The Black Swan: The Impact of the Highly Improbable*, Random House,
Taleb, N.N. (2012), *Antifragile. Things that gain from disorder*. New York: Random House.
Tetlock, Paul C., 2010, "Does Public Financial News Resolve Asymmetric Information?" *Review of Financial Studies* 23, 3520-3557.
Turchin, P. (2005). "Dynamical feedbacks between population growth and sociopolitical instability in agrarian states." *Structure and Dynamics: eJournal of Anthropological and Related Sciences* Retrieved from escholarship.org/uc/item/0d17g8g9.
Turchin, P. (2007), *War and Peace and War. The Rise and Fall of Empires*, New York: Plum (Penguin).
Ulrich, W. (2002), "Boundary Critique". in *The Informed Student Guide to Management Science*, ed. by H.G. Daellenbach and Robert L. Flood, London: Thomson Learning, p. 41f.
Van Rijsbergen, K. (1975), "INFORMATION RETRIEVAL", London: Butterworths.
Von Neumann, J., and Morgenstern, O. (1953). *Theory of games and Economic Behavior*. Princeton U Press.
Waltz, E. and Llinas, J. (1990), *Multisensor Data Fusion*, Artech House, Norwood, MA.
Walsh, M. W., Einstein, E. H., & Gluck, K. A. (re-submitted). A quantification of robustness. Journal of Applied Research in Memory and Cognition.
Wendt, A. (1999). *Social theory of international politics*, Cambridge University Press.
White, D. R. (2007). Innovation in the context of networks, hierarchies, and cohesion. *A new perspective on innovation and social change*. D. Lane, G. West, Sander van der Leeuw & D. Pumain (eds). Dordrecht, Springer Methodos Series.
Wickens, C. D. (1992). *Engineering psychology and human performance* (second edition). Columbus, OH, Merrill Publishing.
Willis, R.P. (2007), "The counterinsurgency pattern assessment (CIPA) program 2007", NRL, p. 2.
WP (2001). European governance (COM (2001) 428 final; Brussels, 25.7.2001). Brussels.
Wolf, F.A., Way, L.W. & Stewart, L. (2010), The efficacy of medical team training: improved team performance and decreased operating room delays: a detailed analysis of 4863 cases, *Annals of Surgery*, 252(3): 477-83; discussion 483-5.

Mathematical Appendix: Interdependence uncertainty relations

With linear algebra (May, 1973), given A as a operator that serves as a community matrix of, for example, possible cooperators within a tribe's ingroup, competitors within a tribe's outgroup, or a comparison of a tribe's cooperators and competitors, let a_{ij}represent the effects of *agent-i* on *agent-j*, and vice versa for a_{ji}; and let ψ be a column vector that represents the state of a social object (individual, group, or a system of tribes). We can measure the effects of a community matrix A from the field. First, accept that competition for resources occurs within and between groups; second, that unlike individuals (Wickens, 1992), the purpose of groups is to multitask (Ambrose, 2001); and third, that the best groups multitask seamlessly, generating a baseline entropy that we arbitrarily set to zero (Lawless et al., 2011). When competition between groups helps a group succeed with its multitasking efforts as it struggles to survive, cooperation increases among its ingroup members (Darwin, 1973; Bowles, 2012). The strength of community matrix A we can measure by its state of interdependence, the effect that a group has on the choices and behaviors of its member; we designate interdependence as ρ, where

$$\rho = (MS_{G/T} - MS_{S/G/T})/(MS_{G/T} + (n-1)MS_{S/G/T}); \quad (3)$$

and $MS_{G/T}$ is the sum of the mean squares from the group on a measurement of an arbitrary factor, issue or problem under review by a group, represented by T (e.g., a plan to address the competition being put into action); $MS_{S/G/T}$ is the aggregated contribution from the individuals on a measurement of the arbitrary factor T; and n represents the number of members in a group being measured (from Kenny et al., 1998; see p. 235). Taken to extremes, ρ can range from -1, as multitasking goes to zero which happens as the effects of a group disappear into a collection of individuals; or ρ can range up to +1, as the effect of the individual disappears in subservience or fealty to the group led a charismatic leader.

Let A be an operator that transforms a state vector ψ into a matrix. Let ψ be a column vector. When ψ is represented on two sides of an equation as $A|\psi>=x|\psi>$, then x is a scalar that is the eigenvalue or characteristic of A, and ψ is then an eigenvector or eigenfunction. The usual way to solve for the eigenvalue, x, is in an iterative process: $A\psi - xI\psi = (A - xI)\psi = 0$, where I is the identity matrix (i.e., $\begin{bmatrix}1 & 0\\ 0 & 1\end{bmatrix}$).

The outer product of two state vectors is an operator; and the outer product of two eigenvectors is a projector, P, a special operator. When P operates on ψ as an unknown or arbitrary state vector, it creates an eigenvalue and eigenfunction. Eigenfunctions are orthonormal; i.e., given eigenfunctions ψ and ϕ and $<\psi|\phi>$ as the inner product of the two eigenfunctions, then $<\psi|\phi>=\psi_1\phi_1+\psi_2\phi_2+...=\delta_{ij}$, where δ_{ij} as the Kronecker delta equals to 1 when $i=j$, otherwise 0. This result means that state vectors are normalized, the inner product summing to 1 when the eigenvectors are the same; it also means that the probabilities of measuring interdependent (or bistable) factors always sums to 1.

If ψ was a simple column vector representing the state of its independent elements, putting aside the mathematical manipulations to find the eigenvalues, there would be little ambiguity in constructing conceptual models. Conceptual difficulties arise when interdependence (groupiness) is introduced. Then ψ becomes a superposition of the two orthogonal states possible for a single individual, such as observation and action; republican and democrat; or a tribal ingroup member and tribal outsider (e.g., Chagnon, 2012). Also putting time evolution aside for this paper, we gain snapshots of a situation by letting $|0>$ be the name of a column vector that represents one of the orthogonal factors of a basis, and $|1>$the other (e.g., we

arbitrarily set observation to $|0>=\begin{bmatrix}1\\0\end{bmatrix}$, and action to $|1>=\begin{bmatrix}0\\1\end{bmatrix}$); or we could let conservatism be represented by $|0>$ and liberalism by $|1>$ (and vice versa); or ingroup *A* versus outgroup *B* (Tajfeld, 1970; for a modern take on Tajfeld, see the special issue in the journal *Science* on human conflict,[78] 2012). Here, $|0>$ and $|1>$ form a basis.

Cognitive dissonance keeps the most important attitudes and beliefs of humans stable (Festinger, 1985), indicating that effort is necessary to change strongly held beliefs (Cooper, 2007), foreshadowing the conflict that spontaneously arises between political parties. It is unlikely that a leader of say the conservatives or liberals would entertain opposing (orthogonal) viewpoints, especially when entertaining such views threatens their power, status or access to resources. Not so for those located farthest from a leadership position or farthest from the control of stable funding, so called "neutral" members or swing voters, those whose beliefs are unstable or malleable. To simplify what constitutes a complexity of its own, assume there are ideologues on either side of an issue, and that all swing voters are ensconced in the neutral camp (see Fig. 4). For those in political swing camps, we postulate that both views are held simultaneously in a state of superposition; likewise for those individuals mindful while in a state of action (viz., not daydreaming, or not in a state of denial about their action, as might be true for alcoholics). In the case of a superposition of orthogonal factors (opposed beliefs; or beliefs and actions), from equation (1), $|\psi>=a|0>+b|1>$, where $|a*a'|=a*a=a^2$ (where a' is the complex conjugate that we use to represent an illusion) gives the probability of a social object being found in state |0>, and with b^2 giving the probability of being in state |1>.

Further, we postulate, there is a constant competition operating between the orthogonal functions for observation and action, orthogonal views like conservatism and liberalism, or

[78] See Riddihough et al.'s (2012), "Introduction, Human Conflict: Winning the Peace", *Science*, 336: 818-19.

orthogonal membership in either tribe *A* or tribe *B*. The competition between these orthogonal functions results in limit cycles[79] (May, 1973; e.g., see Figure 5).

Limit cycles can be suppressed under authoritarian rule. In a dictatorship, control is asserted by censoring information (May, 1973); i.e., by forcibly setting *a* or *b* to zero in equation (1). But while control is gained, the opportunity for mistakes increases dramatically (e.g., DOE's mismanagement of nuclear wastes prior to 1985;[80] China's air[81] and water[82] contamination today; the USS Vincennes shoot-down of an Iranian airbus in 1988, killing all aboard;[83] and the USS Greeneville's collision with a Japanese fishing boat,[84] killing nine of its crewmembers).

Compared to a collection of independent individuals, we have assumed that the entropy (*S*) is set to zero for a perfect team, the driving motivation to form a tribe. We now justify this assumption in the limit as follows. Transaction costs are lower for individuals inside of a firm performing the same functions as those same individuals multitasking in a firm (Coase, 1937). This is also the motivation behind the six-sigma processes designed to reduce waste in a firm, but that adversely precludes the tradeoffs that make it less likely a firm will find the new sources of free energy needed to adapt or to innovate (Christensen, 2011), unexpectedly generating more entropy in a changing environment, setting a firm up for failure.[85]

Equation (2) allows us to capture tradeoffs. When two operators *A* and *B* representing two different tribes have the same eigenvalue, then the operators commute: $[A,B] = AB - BA = 0$.

[79] A limit cycle is the trajectory of a dynamical system's oscillations of periodic behavior(s) caused by the interdependence between at least 2 factors; they can be stable; and they can be beneficial; e.g., *New York Times* (2012, 9/28), "Why the beaver should thank the wolf". Limit cycles reflect a "gap" in social reality, explained in the text.
[80] *New York Times* (1985, 3/17), "Living with nuclear waste".
[81] *New York Times* (2013, 1/14), "China lets media report on air pollution crisis."
[82] *Al Jazeera* (2013, 3/4), "China comes clean on water pollution".
[83] Washington Post (1988, 7/4), "Navy missile downs Iranian Jetliner."
[84] Chicago Tribune (2001, 11/26), "3 investigating Admirals tour USS Greeneville's control room."
[85] Despite its leadership with computer desktop software, Microsoft has failed to successfully develop a mobile device or tablet computer; from *Bloomberg* (2013, 315), "Microsoft's surface tablet is said to fall short of predictions'.

Under this situation of agreement between two competitors,[86] the combined social system is stable, no oscillations occur, nor do limit cycles exist. But when disagreement arises between two competitors, their two operators do not commute, and $[A,B] = iC$. (From Euler's formula, we set i equal to $\sqrt{-1}$; engineers, biologists and physicists use i to model oscillations; the equation for oscillations becomes: $e^{i\theta} = \cos\theta + i\sin\theta$; and $e^{-i\theta} = \cos\theta - i\sin\theta$.) However, as multitasking improves, the tradeoffs between each group's focus on the tasks at hand interferes with the meta-perspective on how best to change or tune those tasks to improve performance (Bloom et al., 2007), motivating the tradeoffs that may or may not be efficacious, reflected in equation (2): $\sigma_A \sigma_B \geq 1/2$ (adapted from Cohen, 1995).

Equations (1) and (2) reflect that a "gap" in social reality exists. This gap promotes illusions (Adelson, 2000), irrationality (Kahneman, 2011), and limit cycles (May, 1973). The evidence indicates that the conscious awareness of signals takes about 500 msecs, but under decision-making, it can extend to several seconds (of at least 7 secs) before a human's consciousness becomes aware of its tendency toward a new choice (Bode et al., 2011) that can then be articulated by the human brain's running narrator (Gazzaniga, 2011).[87]

Despite the accumulating evidence, the traditional model of decisions is rational (e.g., Bayesian). Silver (2012) concludes that the brain forms and continually updates a set of Bayesian "priors" learned over a lifetime used to interpret new data that corresponds to its environment. But Silver has the hindsight of observing the polls with his technique of aggregating polling data. The more important question is why Democrats and Republicans look at the same data but

[86] For example, see agreement between the *New York Times* and *Wall Street Journal* over the pigs found in the river headed to Shanghai; cf. *New York Times* (2013, 3/12), "China: Dead pigs in river near 6,000"; and *Wall Street Journal*, Review & Outlook, Editorial (2013, 3/15), "What's in China's water? Of floating pigs and political change."

[87] Working in the field with teams of robots capable of collectively updating their status, changing roles among their members, and making re-tasking decisions, all in less that one second, the anecdotal evidence indicates that their human operators should not be sent alerts in less than 45 seconds and preferably 90 seconds.

interpret it differently in real time, thereby generating conflict and oscillations. For example, R.A. Fisher, the esteemed statistician and evolutionary biologist (Box, 1978), argued against the evidence that smoking cigarettes would cause cancer; but Fisher was a smoker (Stoley, 1991), likely the cause of his not accepting the available evidence.

We have argued that interdependence combines with cognitive dissonance to make those of us who adopt strong beliefs then act as dictators or police to self-regulate or suppress the alternative views inside of our own ingroups; when these beliefs are unchallenged, they become the source of illusions (Adelson, 2000) that form the oscillations that drive the social behavior between competing teams, tribes, or firms in a system (Lawless et al., 2010). Thus, the presence of alternative views in the decision process is not only the end of certainty that motivates tradeoffs (equations 1 and 2, respectively), but it is also the source of information that competition generates for observers to process that preclude, reduce or mitigate tragedies (e.g., no modern democracy has ever suffered from famine; in Sen, 2000; and modern democracies do not start wars against each other; in Wendt, 1999). For an individual's defense, Chagnon (2012) concluded that people find safety in numbers. However, although not very popular to any single tribe of Republicans or Democrats, competing religions or different races, nonetheless, it is the competition for the strongest idea that has become the modern foundation of free speech (Holmes,[88] 1919).

[88] In his dissenting opinion, Justice Holmes wrote: "when men have realized that time has upset many fighting faiths, they may come to believe even more than they believe the very foundations of their own conduct that the ultimate good desired is better reached by free trade in ideas -- that the best test of truth is the power of the thought to get itself accepted in the competition of the market, and that truth is the only ground upon which their wishes safely can he carried out."